



The Effects of Energy Consumption and CO2 Emissions on Economic Growth: A Panel Cointegration Analysis for BRICS Countries

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Received: 10 March 2024, Revised: 15 July 2024, Accepted: 26 August 2024, Published: 30 September 2026
Publisher: The University of Tehran Press.

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Abstract

The need to ensure the sustainability of natural resources is an environmental issue that occupies a significant place in economies. For this reason, the energy used to produce goods and services reduces a country's economic growth. This study examines the long-term relationship between energy consumption and economic growth in the BRICS countries. The analysis covers a long period from 1995 to 2019. It relies on different econometric techniques, namely panel unit root tests (stationarity) and Kao panel cointegration tests (cointegration). Therefore, to estimate long-run relationships, panel regression estimators, fully modified ordinary least squares and dynamic ordinary least squares estimators are used. The estimation results showed the existence of a cointegrating relationship. Moreover, energy consumption positively affects the economic growth in BRICS countries. In addition, the paper includes a sensitivity analysis that assesses the effect of GDP growth on CO2 emissions in the BRICS countries. It also provides a regression analysis to create an EKC curve. This curve evaluates sensitivity and highlights the impact of renewable energy use in controlling and reducing CO2 emissions, thus confirming the EKC theory. Consequently, it can be concluded that rising CO2 emissions are a major concern for the BRICS countries, leading them to increase biomass energy production. Based on the results, this empirical study suggests implementing strong regulatory policy instruments to increase spending in order to protect economic stability and improve energy efficiency. This empirical study suggests implementing strong regulatory policy instruments to increase spending on protecting economic stability in order to improve energy efficiency.

Keywords: BRICS, CO2 emissions, economic growth, energy consumption, panel data.

JEL Classification: C13, N7, O47, Q4.

Introduction

The degradation of natural resources is an environmental problem that occupies an important place in various economies (Kuang et al., 2023). Additionally, it still has climate change and global warming implications, mainly caused by greenhouse

gas emissions (Nguyen et al., 2023; Voumik et al., 2023). For example, deforestation is exploited for agricultural and commercial purposes. In fact, fossil fuel combustion and human activities contribute to the increase in greenhouse gas emissions, leading to a rise in global temperature (Abernethy and Jackson, 2022).

Coal, natural gas, and crude oil derivatives are natural resources for energy production (Amuda et al., 2023; U-Durar et al., 2023; Guo et al., 2023). On the other hand, carbon emissions destroy the ozone layer, negatively affecting the environment (Kabir et al., 2023). In fact, carbon dioxide is created and emitted when hydrocarbons are used to generate electricity, which subsequently contributes to climate change and, therefore, affects human health (Gür, 2022; Voumik et al., 2023; Saleh and Hassan, 2023). Therefore, numerous standards and regulatory policies are considered to combat global warming (Raihan and Tuspekova, 2022; Gurney et al., 2023).

The increase in human activities due to the onset of industrialization is leading to rapid changes in land use (Chen et al., 2023). These shifts are considered the main reason for the increase in greenhouse gas emissions (Barati et al., 2023; Madronich et al., 2023; Gao et al., 2023). In fact, industrialization nowadays contributes to economic growth in several ways (Vîrjan et al., 2023).

In recent years, the relationship between the environment, energy, and economic growth has received increasing attention (Bhuiyan et al., 2023; Sadiq et al., 2023; Mitić et al., 2023). Previous studies have shown the dynamic nature of this relationship (AlNemer et al., 2023). In fact, using natural resources brings immediate economic benefits, but long-term negative environmental impacts are observed (Li et al., 2023; Yu et al., 2023; Ahmad et al., 2023). Energy is also essential for economic development (Jie et al., 2023). Previous research has also shown that energy consumption has a direct impact on the environment (Wang et al., 2023; Ullah et al., 2023; Chien et al., 2023; Sumaira and Siddique, 2023; Bisset, 2023).

In recent years, numerous scientific studies (Osobajo et al., 2020; Xiaoman et al., 2021; Raihan et al., 2022; Rehman et al., 2022; Liu et al., 2023; Li et al., 2023; Shang et al., 2023; Sadiq et al., 2023; Bhuiyan et al., 2023) have examined the nature of the relationship between energy consumption, economic growth, sustainable development, and carbon emissions.

The implementation of environmental policies and regulations has an impact on improving energy availability in all economies, including the new BRICS economies (Fan and Wang, 2024). The BRICS countries, namely Brazil, Russia, India, China, and South Africa, form a significant demographic, geographic, and

economic bloc. They play an important role in around one-fifth of the world economy (Agarwal and Kumar, 2023).

Statistical Analysis of Data from the BRICS Economies

Over the past few decades, these countries have achieved remarkable economic progress. In fact, in 2023, the BRICS accounted for 36% of global economic output. This is a significant increase compared with 11% recorded in 2005 and 22% in 2016.

The BRICS countries stand out from other developing nations due to their high economic performance and potential. In fact, there are several reasons for choosing the BRICS countries in this article. First, according to BP 2019 data, these countries account for 42.4% of global CO₂ emissions and 36.4% of global renewable energy production. Second, these countries represent around 24% of global GDP (WDI, 2018), giving them considerable economic power. According to the World Bank, China has reached the second position in terms of nominal GDP, followed by Brazil (seventh), India (ninth), Russia (eleventh), and South Africa (thirty-third) (Psacharopoulos et al., 2018). In 2018, the BRICS countries had a cumulative GDP close to that of the United States and are expected to surpass the G7 countries by 2030. Furthermore, China and India have experienced remarkable economic development. The following figures depict the state of the BRICS economies in 2018 (CO₂ emissions, energy consumption, and economic growth).

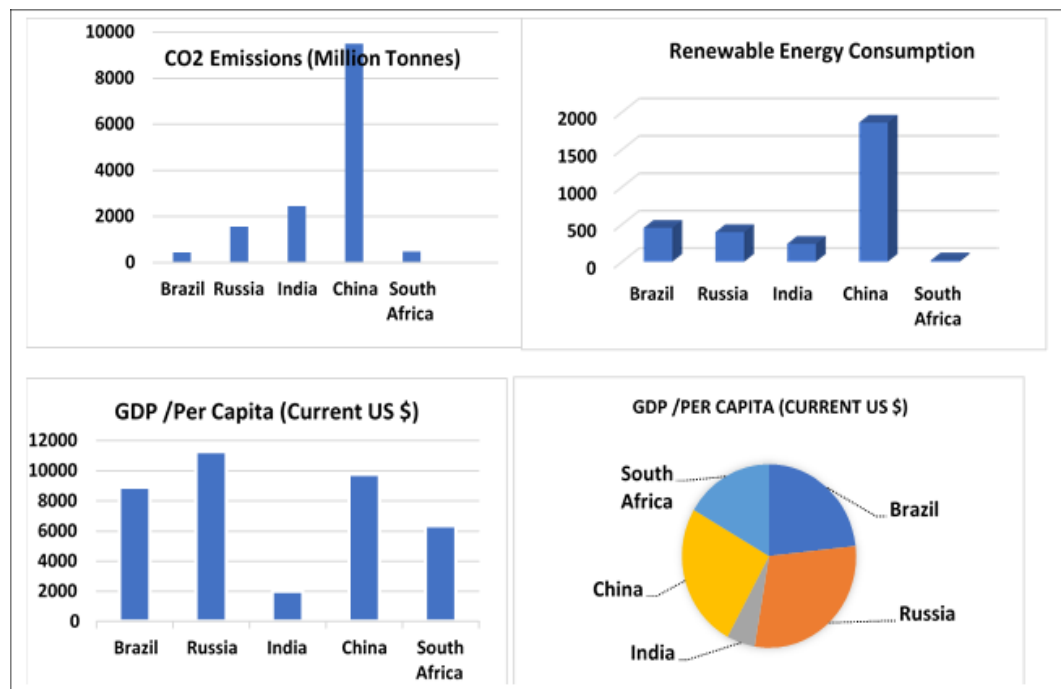


Figure 1. The State of the BRICS Economies in 2018 (CO2 Emissions, Energy Consumption, and Economic Growth)

Source: World Bank and BP Statistics (2019).

Due to their rapid development and large numbers, the BRICS now account for 47% of the world's population. In fact, energy consumption in the BRICS economies is rising every year. On average, these countries represent around 43% of global energy consumption and are heavily responsible for carbon dioxide emissions. Given their significant global impact on CO2 emissions, the BRICS countries were responsible for 41% of global CO2 emissions before 2019. Indeed, Russia is the world's leading resource producer, owning 20% of the world's resources and 97.7% of its domestic wealth. Furthermore, the BRICS economies play an important role in global trade. Indeed, the combined exports of the BRICS countries reached \$4.6 trillion in 2020.

Indeed, according to World Trade Organization data, the BRICS countries export around \$3.49 trillion worth of goods, accounting for 19.3% of the global total. According to Long et al. (2018), China remains the world's leading exporter of around 12.8% of global exports, followed by Russia. These countries possess significant amounts of human capital and natural resources. They also have efficient well-developed education systems that provide industry with skilled labor. Therefore, the BRICS countries must play a vital role in global economic

development in the future. Table 1 presents the socio-economic indicators for the BRICS economies in 2018.

Table 1. Environmental and Socio-Economic Situation of The BRICS in 2018

Indicators	Brazil	Russia	India	China	South.A	World
CO2 Emissions (Million Tonnes)	442.27	1548.39	2452.48	9507.08	470.28	34,007.88
Renewable Energy Consumption	453.12	395.45	238.99	1859.69	18.74	8148.32
GDP Per capita (current US \$)	8920.76	11,288.87	2009.98	9770.85	6374.03	11,372.25
FDI Inflow (Billion \$)	88.32	8.78	42.12	203.49	5.47	1097
Exports (Billion \$)	274.98	507.76	537.04	2651.01	110.07	25.397
Imports (Billion \$)	266.78	344.26	642.70	2548.99	108.88	24.742
Labor Force (in Million)	105.37	73.53	512.35	785.97	22.76	3492
Trade Openness % of GDP	15.80	21.01	11.24	20.47	27.69	59.49

Source: World Bank and BP Statistics (2019).

The main challenge is to understand the fundamental variables that influence economic growth, such as carbon dioxide emissions, renewable energy consumption, exports, foreign direct investment, labor force, and trade openness, which affect economic growth. In fact, positive economic growth can be beneficial.

Moreover, the accession of Argentina, Egypt, Saudi Arabia, Ethiopia, the United Arab Emirates, and Iran to the BRICS group has energy implications (Skaricic, 2023). The expansion encourages new trade relations between the new BRICS countries (Rahman et al., 2023). In fact, Ethiopia occupies a significant position (Gebreluel, 2023) due to its strategic geographical location and key role in the Middle East oil and other commodities trade. Moreover, Egypt is the world's 13th largest producer of natural gas. Its production is greater than that of oil powerhouses such as the United Arab Emirates, Mexico, and Brazil (Escribano and Lázaro-Touza, 2023). Indeed, close cooperation between Saudi Arabia and Russia will be beneficial. If the pipeline project currently under development is completed, Argentina could become a more important player in world natural gas markets (Vilela Pinto dos Anjos et al., 2023).

This article contributes to the existing literature in several significant ways. First, it fills a gap by empirically examining the impact of energy consumption on

economic growth in BRICS countries up to 2019, a relatively recent period. Second, unlike some previous studies that rely solely on time-series data, this study uses panel data to obtain more precise model parameter estimates and a more dynamic understanding of the relationship between energy consumption and economic growth, accounting for heterogeneity across countries. Third, the innovation of this article lies in the use of robust methodologies such as IPS and LLC panel unit root tests, as well as the cointegration approach, which provides robust results despite sample size constraints.

The main findings of this study reveal a negative effect of energy consumption on economic growth, indicating a decline in energy efficiency in the BRICS countries. These findings have important implications for policies aimed at ensuring economic stability and promoting sustainable development, notably by encouraging the transition to renewable energy sources. By providing relevant insights for policymakers, this study significantly contributes to a rapidly developing field, particularly when considering the specific challenges associated with energy transition in the BRICS countries. In addition, the paper includes a sensitivity analysis that assesses the effect of GDP growth on CO₂ emissions in the BRICS countries. It also provides a regression analysis to create an EKC curve. This curve evaluates sensitivity and highlights the impact of renewable energy use in controlling and reducing CO₂ emissions, thus confirming the EKC theory. Consequently, it can be concluded that rising CO₂ emissions are a major concern for the BRICS countries, leading them to increase biomass energy production. Based on the results, this empirical study suggests implementing strong regulatory policy instruments to increase spending in order to protect economic stability and improve energy efficiency.

In particular, this article examines the close relationship between energy consumption and economic growth. Thus, it is organized as follows: The first section is the introduction. The second section presents the theoretical background. The third section deals with the model specification and methodology. The fourth section covers the results and discussions. Finally, the fifth section discusses the results of the study and its recommendations.

Theoretical Background

The recent literature draws on the main results of theoretical and empirical work by several authors (Cetin et al., 2018; Azam et al., 2021; Yang et al., 2021; Bashir, 2022; Raihan, 2023; Liu et al., 2023), who have provided a concise literature on the analysis of the impact of energy consumption on economic growth.

Most studies have examined the impact of renewable energies on environmental pollution using indicators of CO₂ emissions or ecological footprint (Appiah et al., 2023; Caglar and Askin, 2023), which do not consider the fact that pollution is caused by human consumption patterns, and these indicators neglect supply (Saqib et al., 2024; Roy, 2024). However, the study by Pata et al. (2024) uses the CCF (Carrying Capacity Factor) as an environmental indicator. It analyzes the causal relationship between different types of renewable energy in the United States, integrating labor and capital stocks (Altıntaş et al., 2024). Thus, the results show that economic growth depends on renewable energies and that a bidirectional causal relationship exists between total renewable energy, wood, biomass, and economic growth (Perone, 2024; Sarabdeen et al., 2024).

On the other hand, the study by Ritu and Kaur (2024) aims to examine the impact of economic growth and energy consumption on India's ecological footprint over the period 1998-2020. The authors use an autoregressive distributed lag (ARDL) model to test the short- and long-run coefficients and the cointegration of variables (Khan and Sun, 2024; Hazmi et al., 2024). The estimation results show a long-term relationship, meaning that economic growth resulting from a heavy dependence on fossil fuels contributes to environmental unsustainability (Raihan, 2024; Wang and Yang, 2024). However, the results also reveal that education promotes pro-environmental behavior and leads to the adoption of cleaner technologies that enhance environmental sustainability (He et al., 2024).

Hussain et al. (2023) shows that increasing renewable energy and carbon emissions lead to better long-term economic growth (Madaleno and Nogueira, 2023; Jain et al., 2023; Ali et al., 2023) for a sample of 133 Belt and Road Initiative countries. However, increasing non-renewable energy caused a slowdown in GDP per capita growth between 1996 and 2020 (Husaini et al., 2024). The authors used quantile regression and modified ordinary least squares estimation techniques (Khan and Hassan, 2024; Veeravel et al., 2024). Their results agree with previous research showing the close relationship between energy consumption and economic growth.

Al-Mulali et al. (2013) conducted a study on the impact of renewable energy consumption on GDP growth for countries classified into three income classes (high, medium, and low). They used the FMOLS procedure between 1980 and 2009, with renewable electricity consumption and GDP as study variables. They demonstrated that 79% of the data, especially in high-income countries, showed a positive long-term bidirectional causality. However, they found no causal

relationship for 19% of these countries. For the remainder, there was a unidirectional relationship between GDP and renewable electricity consumption.

Maji et al. (2019) estimate the impact of renewable energy on economic growth in West African countries using dynamic ordinary least squares (DOLS) on a sample of 15 West African countries covering the period 1995-2014. They show that consuming renewable energy slows down economic growth in these countries.

The role of the digital economy in developing renewable energies is still limited. In this regard, the study by Zheng and Wong (2024) shows how the amplification of the digital economy affects renewable energies in China (Song et al., 2024; Fang et al., 2024). The authors used a fixed-effects model to obtain good results (Alsamara et al., 2024). The estimation gives a positive relationship between the digital economy and the development of renewable energies (Wang et al., 2023; Xin et al., 2024; Xue et al., 2024). In more detail, the positive influence of the digital economy on hydropower (Hancock and Sovacool, 2018) is justified by the intervention of the government to support the positive association between the digital economy (Liang and Li., 2023) and hydropower development in the central and western governorates (Fan et al., 2023).

Bhattacharya et al. (2016) study the contribution of renewable energy to the economic development process in 38 countries between 1991 and 2012. They use panel cointegration methods (FMOLS and DOLS) and heterogeneous causality analysis on variables such as GDP, gross fixed capital formation, labor, and renewable and non-renewable energy consumption. They conclude that in the long term, renewable energy should be integrated into the energy production cycle to ensure sustainable development and economic stability. In addition, they examine the causality between GDP and renewable energy consumption. In fact, they demonstrate a positive relationship for Austria, Bulgaria, Canada, Chile, China, the Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Kenya, South Korea, Morocco, the Netherlands, Norway, Peru, Poland, Portugal, Romania, Spain, and the United Kingdom. However, the relationship between GDP and renewable energy consumption is negative in India, Ukraine, and the USA.

To detect any potential impact of the uncertainty index on carbon dioxide (CO₂) emissions in selected MENA countries, Ayad et al. (2023) used various models such as the ARDL model and its extensions such as augmented ARDL models, augmented NARDL models, and MTNARDL models. The results show that the uncertainty index increases environmental degradation, especially in

Morocco, Turkey, and Iran, if the resulting changes are followed (Wan et al., 2024; Ali et al., 2024). Furthermore, the same results reveal that energy consumption and population size increase CO2 emissions (Raihan, 2024; Nuță et al., 2024).

Wang et al. (2022) consider energy as the oxygen of an economy, fueling all economic activities. Therefore, they empirically analyze the relationship between fossil energy consumption and economic development in the case of BRICS countries between 1990 and 2019. The authors use fully modified ordinary least squares methods to assess the size effect over time. The results show that coal and natural gas consumption follow an inverted U-shaped relationship with HDI, while coal consumption exhibits a negative relationship with HDI. Thus, coal and gas contribute to development when their share is low, while overconsumption hampers development. The authors conclude that BRICS countries should optimize coal and gas consumption according to economic growth.

Methodology

Model

This study has three objectives: The first is to examine the impact of energy consumption on GDP per capita. The second is to investigate the effect of energy consumption on CO2 emissions for the BRICS economies between 1995 and 2019. The third is to analyze the sensitivity of CO2 emissions to economic growth to determine whether the Kuznets theory applies to the BRICS countries. Therefore, it is important to note that the literature has added a dimension to the growth model by incorporating energy consumption, which could represent the correlation between gross domestic product (GDP) and renewable energy consumption (REC). This allows us to build on research by Apergis and Payne (2009), Solarin and Shahbaz (2015), Sofiane (2021), and Gershon et al. (2024). We chose the following variables to examine this relationship: real GDP per capita (GDP), renewable energy consumption (REC), foreign direct investment (FDI), population growth (POP), public expenditure (GE), Gross fixed capital formation (GFCF), and trade openness (Trade).

The study requires the analysis of the following models. Model (1) will be used to determine the relationship between economic growth and the use of renewable energies.

$$GDP_{it} = f(REC_{it}, FDI_{it}, POP_{it}, GFCF_{it}, Trade_{it}, GE_{it}) \quad (1)$$

The form of the model is expressed as follows:

$$GDP_{it} = \alpha_0 + \alpha_1 REC_{it} + \alpha_2 FDI_{it} + \alpha_3 POP_{it} + \alpha_4 GFCF_{it} + \alpha_5 Trade_{it} + \alpha_6 GE_{it} + \mu_i + \varepsilon_t$$

where i denotes the country and t is the period. We use real GDP per capita (GDP) in constant 2010 US dollars as a measure of economic growth, and renewable energy consumption (REC) measured in kilowatt-hours per capita as the net consumption of geothermal, solar, wind, biomass, and residual electric power. Sadorsky (2009) and Apergis and Payne (2010) used the same measure for renewable energy consumption. Therefore, a positive sign is expected.

Then, Gross Fixed Capital Formation (GFCF), measured in % of GDP, serves as a proxy for economic growth and Apergis and Payne (2010) support this finding. Therefore, a positive sign is expected. In addition, trade openness (Trade), measured by exports and imports as a percentage of GDP, is a crucial indicator for the BRICS countries, as it emphasizes the importance of focusing more on exports to stimulate economic progress in these nations. These findings align with the research conducted by Sultanuzzaman et al. (2019) and Upreti (2015). Therefore, a positive sign is expected in this study.

According to neoclassical theory, Foreign Direct Investment (FDI) contributes to economic growth by increasing capital accumulation per capita and optimizing investment (Mahembe and Odhiambo, 2014; Das and Sethi, 2020; Rao et al., 2020). Duodu and Baidoo (2022) confirm this hypothesis. Thus, a positive trend is expected in this study.

Furthermore, economic players consider population growth (POP) as one of the most crucial and feared macroeconomic variables because it explains that population growth leads to economic growth (Brida et al., 2024; Yunker, 2024; Rahman et al., 2020). These studies have confirmed the beneficial effect of population on economic growth.

Theoretically, several authors have proven the relationship between public spending and economic growth. In fact, Adebayo and Samour (2024), Attari and Javed (2013), Leshoro (2017), and Kimaro et al. (2017) confirmed that public spending has a positive impact on economic growth. Therefore, the sign should be positive. In fact, all this data is obtained from the World Development Indicators (WDI) online database published by the World Bank (2023).

Since the second objective is to study the impact of energy consumption on CO₂ emissions, the second model was constructed. This model aims to analyze the relationship between carbon dioxide emissions and the consumption of renewable energy sources. Contrary to common belief, although the carbon footprint of renewable sources is minimal, even neutral in some cases, their use in domestic and industrial settings still creates a significant carbon footprint. The model is expressed as follows:

$$CO2_{it} = f(GDP_{it}, REC_{it}) \quad (2)$$

The form of the model is expressed as follows:

$$CO2_{it} = \alpha_0 + \alpha_1 GDP_{it} - \alpha_2 (GDP_{it})^2 - \alpha_3 REC_{it} + \varepsilon_t$$

In the equation above, *i* denotes the country, and *t* is the period. According to the EKC hypothesis, the coefficient α_1 should be positive, and the coefficient α_2 is anticipated to have a negative sign. At the same time, the significance and negativity of the coefficient imply the presence of an inflection point on the curve. At this point, increased economic growth begins to reduce CO2 emissions. However, when the coefficient α_2 is not significant, CO2 emissions increase monotonically. Indeed, we use CO2 emissions to denote CO2 emissions resulting from energy consumption, expressed in metric tons per capita. GDP represents economic growth, and REC represents the use of renewable energy.

In Model (2.2), CO2 emissions are considered the dependent variable and expressed in tons, which is considered an international standard measure. CO2 symbolizes the number of pollutants produced, as it is also deemed the primary contributor to global warming and environmental degradation. Therefore, measuring the negative impact of GDP growth on the environment is essential. Meanwhile, we include GDP per capita as a key variable in the study, as it represents the nation's economic growth and social well-being and is measured in US dollars. The reason for including $(GDP)^2$ as a variable is to enable the construction of the Brundtland curve or the Kuznets curve, both of which are polynomial. These curves allow us to assess the sensitivity of GDP growth to the increase in CO2 relative to GDP growth. The variables used in this model for estimation purposes, along with their definitions, measurements, and sources are shown in Table 2.

Table 2. Variable, Description, Source, and Units of Measurement

Variable	Description	Source	Units of Measure
GDP	Economic Growth	WDI	GDP per capita growth (annual %)
REC	Energy Consumption	WDI	Electric power consumption (kWh per capita)
GE	Government Expenditure	WDI	Government final consumption as a % of GDP
POP	Population Growth	WDI	Population growth (annual %)
FDI	Foreign Direct Investment	WDI	net investment flows as % of GDP
Trade	Trade Openness	WDI	Merchandise trade (% of GDP)
GFCF	Gross fixed Capital Formation	WDI	Gross fixed capital formation % of GDP
CO2	CO2 emissions	WDI	CO2 emissions (metric tons per capita)

Analysis of Statistical Properties

Descriptive Statistics and Correlation

The descriptive statistics summarize the mean, maximum, minimum, and standard deviation values of the different variables used in the panel data. Table 3 shows that GDP has a mean of 3.47, ranging from a minimum of 3.34 to a maximum value of 3.634 and that its volatility is very low (Std. Dev = 0.11963). In addition, the average growth rate of renewable energy consumption per capita is equal to 3.146 for the REC variable. The range of renewable energy consumption is between a minimum of 2.789 and a maximum of 4.678, with a very low standard deviation of 0.134. On the other hand, FDI is characterized by an average of 1.402, ranging from a minimum of 1.33 and a maximum of 1.46. This shows that FDI in the BRICS region is significant and is a source of economic growth. Thus, the BRICS countries have high public spending, with a high average equal to 0.796 and a low variability of 0.085. The same analysis applies to population growth, with an increase in the BRICS countries' population contributing to higher economic growth since the minimum is 6.97. As for Skewness, we notice that REC and GDP are positively asymmetrical and spread to the left, but the other variables are positively asymmetrical and spread to the right. In terms of kurtosis, we find that the distribution is less flattened than the normal distribution and that the observations are more concentrated.

Correlation tests measure the strength of the relationship between variables (Schober et al., 2018; Senthilnat, 2019). They determine whether there is a correlation between variables and the type of this correlation if so. The results presented in Table 4 show a negative correlation between GDP and REC, with a value of -0.821. However, the correlation between population and energy consumption remains negative. On the other hand, positive correlations occur between FDI, GE, POP, Trade, GFCF and CO2 and GDP, which justifies the strength of the relationship between these macroeconomic variables and economic growth in these countries.

Table 3. Summary Statistics of the Variables

	GDP	REC	POP	GE	FDI	Trade	GFCF	CO2
Mean	3.479	3.146	7.003	0.795	1.402	2.369	2.156	1.035
Median	3.466	3.569	6.999	0.685	1.397	2.213	3.568	1.159
Maximum	3.634	4.678	7.043	0.935	1.465	2.879	4.256	1.258
Minimum	3.344	2.789	6.978	0.639	1.336	-1.239	-1.584	0.265
Std. Dev.	0.119	0.134	0.022	0.085	0.033	0.153	0.125	0.056
Skewness	-0.188	0.552	0.400	0.375	0.407	-0.422	0.456	-0.247
Kurtosis	1.277	2.026	1.798	2.699	3.010	1.256	1.568	1.589

Source: Research findings, using EViews.

Table 4. Correlation Test

	GDP	REC	Pop	FDI	GE	Trade	GFCF	CO2
GDP	1							
REC	-0.821	1						
POP	0.951	-0.945	1					
FDI	0.658	0.134	0.720	1				
GE	0.586	0.660	0.599	0.390	1			
Trade	0.458	0.856	0.698	0.968	0.369	1		
GFCF	0.695	0.568	0.458	0.759	0.678	0.654	1	
CO2	0.365	0.811	0.821	0.748	0.956	0.541	0.847	1

Source: Research findings, using EViews.

Unit Root Test

Recent advances in panel data, particularly concerning stationarity (Phillips and Moon, 2000; Lau et al., 2019), show that panel unit root tests are more robust than those based on individual time series (Okunade and Karakus, 2001; Breitung and Pesaran, 2008). First-generation tests are mainly based on the assumption of cross-sectional independence (Hurlin and Mignon, 2007). Among the most sophisticated tests at this level, we can mention the unit root tests of Im et al. (2003) that consider heterogeneity (Pesaran, 2007; Breitung and Pesaran, 2008). In addition, the LLC test (2002) assumes a homoscedastic unit root (Cavaliere, 2005; Westerlund and Blomquist, 2013).

Breitung test (2001) and Al-Hadri test (2000) are based on the null hypothesis of reliability (Pettersson, 2008). This Lagrange multiplier test aims to test the null hypothesis of stationarity (Kwiatkowski et al., 1992; Harvey, 2005; Dare et al., 2022). In this step, among recently developed tests, we use the unit root tests of IPS (2003) and LLC (2002).

The LLC (2002) unit root tests are an extension of the ADF test to the dynamic panel. These are performed according to the following equations:

$$\Delta y_{it} = \rho_i y_{it-1} = \sum_{s=1}^{\rho_i} y_{is} \Delta y_{it-s} + \mu_{it} \quad (3)$$

$$\Delta y_{it} = \alpha_i + \rho_i y_{it-1} = \sum_{s=1}^{\rho_i} y_{is} \Delta y_{it-s} + \mu_{it} \quad (4)$$

$$\Delta y_{it} = \alpha_i + \beta_{it} + \rho_i y_{it-1} = \sum_{s=1}^{\rho_i} y_{is} \Delta y_{it-s} + \mu_{it} \quad (5)$$

or $\mu_{it} \in \text{iid}(0, \sigma_{\mu}^2)$, the order of differentiation is unknown ($\rho_i=0$), so Levin et al. (2002) assumed a method based on the estimation of the autoregressive unit root, the proportions of individual variances and the construction of Levin's test statistic.

To estimate $\rho=0$ in the unit root estimation step, we calculated the T-stat under the null hypothesis $\{H_0 = 0\}$, thus achieving a common unit root for all individuals and stationary. However, the problem of homogeneity of the autoregressive unit root of the hypothesis leads to the stability of all series.

Indeed, the IPS test (2003) solves problems of unit root homogeneity. The form is written as follows:

$$\Delta y_{it} = \alpha_i + \rho_i y_{it-1} + \varepsilon_{it} \quad \text{or} \quad \varepsilon_{it} \in \text{iid}(0, \sigma_{\varepsilon}^2) \quad \alpha_i = -y_i \rho_i \quad \text{with} \quad y_i \in \mathbb{R}$$

The IPS test is a test of unit root ($\rho_i = 0$) and no individual effect ($\alpha_i = 0$). It is based on the following assumptions: $H_0: \rho_i = 0 \forall i = 1 \dots N$, $H_1: \rho_i < 0 \forall i = 1 \dots N$ and $H_2: \rho_i = 0 \forall i = 1 \dots N+1$. Under the null hypothesis, the IPS test is always a joint test since the nullity of ρ_i implies the nullity of the individual effects. Therefore, under the alternative hypothesis, the process is constant for a small number of individuals. In fact, to perform this test, IPS follows the following test statistic: $T\text{-bar} = \sum_{i=0}^n t_{iT}$ with t_{iT} . With the Student statistic added to the hypothesis ($\rho_i = 0$), this test is determined by the mean of the individual ADF statistics.

Table 5 summarizes the results of the Im et al. (IPS) and Levin-Lin-Chu (LLC) tests applied to the different variables in the model. The results of the unit root tests reveal that at the 1% threshold, four of the six variables are at a constant level (GDP, REC, POP, CO2, Trade, and GE). The non-stationary series (FDI and GFCF) have no unit root as their probabilities are higher than the 1%, 5%, and 10% thresholds. This is why we conclude that the series in question is not constant in level but is constant after differentiation. In reality, it indicates that all series are invariant after differentiation. It is, therefore, a first-degree integral $\{I(1)\}$. We can also highlight the efficiency and robustness of panel unit root tests since after a first differentiation, the series is stationary either to the model with a trend and stationary or about the model with a stationary or non-stationary and no trend.

Table 5. Unit Root Test Results

	Levin-Lin-Chu (LLC)		Im, Pesaran et Shin (IPS)		Stationnarité
	T-stat	Prob	T-stat	Prob	
GDP	-6.351	0.004	-0.687	0.001	I (0)
REC	-15.6226	0.000	-8.5262	0.000	I (0)
POP	-13.416	0.000	-14.580	0.000	I (0)
FDI	4.870	0.425	2.120	0.879	I (1)
	20.387	0.001	-6.489	0.000	
GE	-16.567	0.000	-9.791	0.000	I (0)
CO2	-12.256	0.000	-5.256	0.000	I (0)
GFCF	3.660	0.315	1.425	0.756	I (1)
	18.568	0.000	-6.356	0.000	
Trade	6.258	0.000	2.256	0.000	I(0)

Source: Research findings, using EViews.

Cointegration Test

The study of cointegration relies on the methodology proposed by Kao (1999) based on the Lagrange multiplier residual test, which can be compared with the Shen (1994) test developed for the case of time series. Furthermore, given our sample size, Kao's test allows us to obtain robust results, as this methodology is more suitable for small sample sizes.

Table 6 summarizes the results of the cointegration test performed by Kao (1999) on heteroscedastic panel data. The results show that the probability associated with the T-statistic is significant at the 1% level, which indicates the need to reject the null hypothesis as there is no cointegration and, therefore, a cointegrating relationship exists between the variables in the model.

Table 6. Kao Cointegration Test Results

Indicator	T-statistic	Prob
ADF	-5.62682	0.000*

Source: Research findings.

Note: * Significance of 1%.

Estimating Long-Term Relationships

The long-term relationships between energy consumption and economic growth are identified in the following steps: First, we examine the stability of the variables. Then, to verify the existence of a long-term relationship between the variables, we study cointegration. Finally, if the hypothesis of variable cointegration is confirmed, we use long-term estimates based on the Fully Modified Estimator (FMOLS) and the DOLS (Dynamic Ordinary Least Squares). To demonstrate the existence of a complementary relationship, Chiang et al. (2001) proposed two methods, FMOLS and DOLS.

The FMOLS method studies second-order resource completion problems generated by the correlation between cointegrating residuals and innovations in variables I (1). The FMOLS estimator is given as follows:

$$\hat{\beta}^{\text{FMOLS}} = N^{-1} \sum_{i=1}^n \left| \left(\sum_{t=1}^T \hat{x}_{it} x_{it} \right)^{-1} \left(\sum_{t=1}^T \hat{x}_{it} y_{it}^* - T \widehat{\gamma}_{1t} \right) \right| \quad (6)$$

y_{it}^* is a vector of regressors adjusted by the covariance between the error term and the vector x_{it} . Thus, $T \widehat{\gamma}_{1t}$ represents the adjustment due to the presence of the constant term. The term in brackets is the country-specific estimator of fundamentals.

The DOLS method introduces lagged values of ΔX_{it} in the cointegration relationship in order to exclude the correlation between the expressive variables and the error term (Olorogun, 2023). As a result, the DOLS estimator is the following:

$$Y_{it} = \alpha_i + \beta X_{it} + \sum_{j=-r_1}^{r_2} C_{ij} \Delta X_{it-j} + \varepsilon_{it} \quad (7)$$

Similarly, Cao and Chiang (2001) recognized the usefulness of the DOLS estimator as the most effective method for estimating cointegration relationships in panel data.

Results and Discussion

The DOLS (Dynamic Ordinary Least Squares) and FMOLS (Fully Modified Ordinary Least Squares) methods are used in this study to estimate long-term cointegration relationships between variables. They are also used to correct for simultaneity and endogeneity biases in cointegration models and test the robustness of our findings. The following table summarizes the estimation results of the relationship between energy consumption and long-term economic growth in the BRICS countries using FMOLS and DOLS.

With cointegration revealed, long-run elasticity can be measured in the table below.

Table 7. Panel Regression Results

FMOLS			DOLS	
Model (1): $GDP_{it} = f(REC_{it}, FDI_{it}, POP_{it}, GFCF_{it}, Trade_{it}, GE_{it})$				
Variable	Coefficients	P-Value	Coefficients	P-Value
REC	0.6351	0.0001*	0.5265	0.0000*
FDI	0.4256	0.0000*	0.4892	0.0723***
POP	0.0562	0.0701***	0.0256	0.0000*
GFCF	0.2028	0.0002*	0.2025	0.0000*
Trade	0.1256	0.0000	0.0975	0.0000
GE	0.6012	0.3566	0.5341	0.0002*
R –squared	0.8659		0.8423	
Model (2): $CO2_{it} = f(GDP_{it}, REC_{it})$				
FMOLS			DOLS	
Variable	Coefficients	P-Value	Coefficients	P-Value
GDP	0.401	0.0000*	0.370	0.0000*
REC	0.154	0.006***	0.142	0.0000*
R –squared	0.5236		0.5014	

Source: Research findings, using EViews.

Note: *, **, and *** significance at the 1%, 5%, and 10% levels.

Table 7 presents the results of the FMOLS and DOLS estimations. To start with, it is crucial to note that the R square shows that the variance of the endogenous variables explains 52% of the variance of the exogenous variable for model (1) and 50% for model (2). Therefore, although the estimation techniques differ considerably, our estimation results are significant because they show a strong relationship between energy consumption and economic growth. We observe that the coefficients estimated by the FMOLS and DOLS methods are successively identified in the long term among the different model variants.

The positive sign of the coefficient means that renewable energy consumption positively affects GDP ($\alpha_1 = 0.635$) Androniceanu et al. (2023) and Aslan et al. (2024) demonstrate this idea. Indeed, the analyses indicate that a 1% increase in renewable energy consumption leads to a 63.5% increase in GDP per capita in the long term. However, in the case of DOLS, the estimations indicate that a 1% increase in renewable energy consumption improves GDP by 52.6%. This is explained by the nature and source of renewable energy used in BRICS countries, which is primarily biomass used in China for electricity production. In this context, Ganda et al. (2024), Maji et al. (2019), Bhattacharya et al. (2016), and Gershon et al. (2024) confirmed this conclusion. However, renewable energy consumption can be explained as a source of heat in industry and agriculture, which is often impure and highly polluting when burnt.

Energy consumption theory and economic growth theory were used to empirically analyze this study. According to these theories, all economic benefits can be offset by the cost of using energy resources in production processes. According to Adewyi and Awodumi (2017), energy also plays a crucial role in the production process. Thus, the greater the use of energy in producing goods and services, the higher its contribution to the gross domestic product (GDP) of the BRICS countries.

The FMOLS estimation results indicate that the coefficient on long-term foreign direct investment is positive ($\alpha_2 = 0.4256$) and significant at the 1% level. This indicates that a 1% increase in FDI generates a 42.56% increase in economic growth (Shokhruk et al., 2023; Raihan, 2024; Ghorbal et al., 2024). However, DOLS estimates indicate that a 1% increase in FDI increases GDP by 48.92%.

In this context, BRICS countries must remove barriers to foreign investments to achieve more sustained and sustainable economic growth. These findings are consistent with prior research by Das and Sethi (2020), Rao et al. (2020), and Duodu and Baidoo (2022). However, studies by Sahoo and Sethi (2017) have shown a notable negative impact of FDI on economic growth in India.

Furthermore, the estimated long-run population coefficient is positive ($\alpha_3 = 0.0562$) and significant at the 10% level, meaning that a 1% increase in population leads to a 0.56% increase in economic growth (Uzlu, 2024; Lal, 2023). However, in the case of DOLS, estimates indicate that a 1% increase in population increases GDP by 0.25%. Brida et al. (2024), Yunker (2024), and Rahman et al. (2020) demonstrate the positive effects of population growth. In the same context, Kuznets (1976) indicates that a larger population was associated with higher population growth rates, robust technological advancement, improving labor productivity, per capita income, and standard of living. However, to meet essential needs such as cooking, heating, transport, and electricity, energy demand is also increasing (Mubarak et al., 2020; Befikadu, 2023). In this situation, Ojekemi et al. (2023) demonstrated that population growth in the BRICS countries can increase energy consumption as more people require energy services.

The coefficient of real gross fixed capital formation has a positive effect ($\alpha_4 = 0.2028$). The results indicate that a 1% increase in real gross fixed capital formation increases real GDP by 20%. Apergis and Payne (2010) confirm this. Therefore, gross fixed capital formation is an important factor in the growth of BRICS economies.

The results also demonstrate that trade openness has a significantly positive effect ($\alpha_5 = 0.1256$) on economic growth. This underscores the need for BRICS economies to focus on exports to boost their economic progress. To accomplish this, these countries need to implement flexible policies that promote the export of goods and services. These findings align with Sultanuzzaman et al. (2019) and Upreti (2015).

Finally, the coefficient of public spending has a positive but insignificant effect ($\alpha_6 = 0.6012$). However, the DOLS method shows that a 1% increase in public expenditure decreases GDP by 53.41%. In fact, Javed (2021) and Adebayo et al. (2024) demonstrate this. Indeed, Le et al. (2024) agree that according to neoclassical theory, public spending has perverse effects on economic growth, as it generates budget deficits that reduce private investment. In this context, Bankole and Adesanya (2024) confirm that public spending positively affects economic growth.

The results from Model 2 indicate that a 1% increase in GDP leads to a 40% (FMOLS) and 37% (DOLS) increase in CO2 emissions. On the other hand, a 1% increase in renewable energies results in a mere 0.15% (FMOLS) and 14% (DOLS) increase in CO2 emissions. Overall, the results from Model 2 suggest that renewable energies contribute to CO2 emissions relative to GDP. Both the DOLS

and FMOLS tests confirmed that using renewable resources aids in GDP growth and leads to an improvement in CO₂ emissions.

Sensitivity Analysis

Sensitivity analysis of BRICS countries using Model 3 indicates a positive relationship between GDP growth and CO₂ emissions. These results unsurprisingly suggest that as national output increases in the BRICS countries, the amount of CO₂ emissions also increases due to growing industrial and economic activity. The model statistics are provided in Table 8.

Table 8. Cross-Sectional Regression Analysis Results

Dependent Variable CO₂ Emission Level	
Independent Variable	Estimated Coefficient (Standard Error)
Constant	3.09467 *** (0.917624)
GDP	0.012876 *** (3.780941)
GDP ²	-1.385695 ** (4.856947)
Mean dependent var	0.256361
Renewable Energy Consumption	-0.03441582 *** (0.1031282)
R-squared	0.52468
Adjusted R-squared	0.495507
P-value	2.06408

Source: Research findings, using EViews.

Note: * = Significance at 1% level, ** = Significance at 5% level, and *** = Significance at 10% level.

After a certain level, this relationship becomes negative, suggesting a polynomial form similar to the inverted U curve of the EKC, known as the turning point. This implies that using renewable energy sources increases GDP, resulting in a negative relationship between CO₂ emissions and GDP growth, as the findings show. According to the survey, adopting renewable energy sources significantly reduces CO₂ emissions. The study results indicate that using renewable energy sources has a positive environmental impact in terms of carbon emissions, as they emit less than fossil energy sources. It also yields economic benefits. Thus, this study confirms the importance of renewable energies for economic development while mitigating global CO₂ emissions. The promising results of both tests signal a bright future for renewable energies, as they ensure sustained economic growth much faster than traditional sources and have minimal environmental impact.

Therefore, we can conclude that green economic growth in the BRICS countries can easily be supported by using renewable sources.

Conclusion and Policy Implication

Ensuring the sustainability of natural resources is a major environmental challenge that plays a crucial role in the world's economies. The literature on the links between economic growth and energy consumption has multiplied in recent years. However, to our knowledge, no study has examined the impact of renewable energy consumption on economic growth in the BRICS countries over the period 1995–2019 using various dynamic panel techniques such as stationarity, cointegration, FMOLS, and DOLS. The estimation results suggest that demographics, foreign direct investment, trade openness, gross fixed capital formation and public expenditure have a positive and significant impact on long-term economic growth. The results also show that energy consumption has a positive and significant impact on long-term economic growth. Indeed, a 1% increase in energy consumption reduces long-term economic growth in the BRICS countries by 63.6%. This is due to the nature and source of the renewable energy used in these countries, which is primarily biomass. The latter is used in China for electricity production and as a heat source in industry and agriculture and which is generally impure and highly polluting when burnt. On the other hand, using clean energy sources such as solar, wind, and hydroelectric power, which have no adverse effects on human health or the environment, is lower in this region. Thus, using renewable energies can slow economic growth by reducing productivity when impure and inefficient sources are used.

The sensitivity analysis results show that as economic growth increases, i.e., when GDP per capita rises, CO₂ emissions also grow due to increased economic and industrial activity, representing a significant positive relationship. On the other hand, the EKC curve demonstrates that when these economies reach a certain level of economic growth in terms of GDP per capita, this relationship becomes negative as these countries continue to increase the use of renewable energies, which would reduce their carbon footprint since the consumption of renewable energies significantly reduces CO₂ emissions.

By implementing concrete and achievable recommendations, BRICS countries can be leaders in promoting sustainable development and energy efficiency and combating climate change, thereby contributing to a more sustainable future for succeeding generations. (i) Develop incentive policies: BRICS governments should implement incentive policies, such as subsidies and

tax incentives, to encourage adopting eco-energy technologies and using renewable energies. (ii) Investing in research and innovation: It is essential to invest in the research and development of clean and sustainable technologies to improve energy efficiency and reduce greenhouse gas emissions in key sectors such as industry, transportation, and construction. (iii) Strengthen sustainable infrastructure: BRICS countries should invest in sustainable infrastructure such as smart grids and eco-friendly public transportation to reduce dependence on fossil fuels and promote a transition to cleaner energy sources. (iv) Raising awareness and educating: It is crucial to raise awareness of the importance of energy efficiency and sustainable development among the public and businesses. Information campaigns and educational programs can encourage the adoption of more sustainable behaviors and practices.

Like all research, this one has certain limitations. Admittedly, the method of empirical analysis makes it possible to analyze a large volume of data, and to compare the results obtained, but it suffers from a lack of comparison between countries and groups of countries through the sampling method. However, some points must be deepened to extend this work. It is necessary to integrate other institutional variables to improve the robustness of the results obtained. It is also crucial to study the causality between the variables in the model. These are two avenues that researchers could explore in future research.

To better explain the importance of this subject it would be interesting to conduct another research while trying to use a model that integrates other independent variables and to distribute the sample by country. Thus, our study is only the beginning of a line of research. We hope, through this research, to have at least introduced the subject and to give enthusiasm to other research to embark on this field.

Statements and Declarations

- Funding: This work does not receive any funding.
- Conflict of interest: The authors declare that there is no conflict of interest.
- Consent to Participate: The authors have approved and consented to the manuscript submission.
- Consent to Publication: The authors have given their consent for the publication of the manuscript.
- Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

- Availability of Data and Materials: Data is available on request from the authors.

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Cite this article: Kaddachi, H., & Ben Zina, N. (2026). The Effects of Energy Consumption and CO₂ Emissions on Economic Growth: A Panel Cointegration Analysis for BRICS Countries. *Iranian Economic Review*, 30(3), 1162-1195.