Original Article

ENERGY & ENVIRONMENT

Energy & Environment
1–26

DOI: 10.1177/0958305X251315407
journals.sagepub.com/home/eae
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Role of environmental policy stringency, energy transition, and income in ensuring low-carbon environment: A time-frequency analysis

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Abstract

Public interest concerning the environmental progress of economies has been developing across societies and countries. Such awareness requires dealing with energy, environment, and economic sides altogether. By considering this reality, this research investigates that how there is an effect of environmental policy stringency (EPS), energy transition index (ETI), and income (gross domestic product, GDP) on CO_2 emissions. In doing so, the research analyzes BRICS countries, which are leading developing countries causing high emissions and consuming large amounts of energy, uses data between 2000/Q1 and 2020/Q4, and uses wavelet local multiple correlation approach to analyzes the nexus across times and frequencies. The results demonstrate that (i) EPS declines CO_2

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emissions in Brazil at low and high frequencies; (ii) GDP curbs CO_2 emissions in India at high frequencies; (iii) across remaining times and frequencies, EPS, ETI, and GDP have a mixed effect in BRICS countries; (iv) based on four-variate cases, EPS, ETI, and GDP have an increasing combined effect on CO_2 emissions across all times, frequencies, and countries; (v) the most dominant factor differs according to frequencies and countries, where ETI is mainly leading in Brazil, Russia, and India, EPS is pioneering in South Africa, and China has a mixed situation. Thus, the research empirically proves the diverging effects of EPS, ETI, and GDP on CO_2 emissions across times, frequencies, and countries.

Keywords
Environmental policies, energy transition, income, CO_2 emissions, BRICS, time-frequency analysis

Introduction

CO_2 emissions are a major factor in ecological deterioration, mainly because they greatly contribute to climate change. Increasing quantities of CO_2 emissions in the atmosphere directly contribute to the escalation of global temperatures.[1] This, in turn, results in alterations in weather patterns, more frequent and severe heatwaves, modifications in precipitation patterns, and a rise in sea levels. The alterations have a disruptive effect on ecosystems, posing a threat to species that rely on certain climatic conditions for their existence. Additionally, they contribute to a rise in severe weather phenomena. The burning of fossil fuels for electricity generation, transportation, industrial operations, and deforestation activities results in the emission of significant quantities of CO_2 into the atmosphere. The emissions have significantly disrupted the natural carbon cycle, leading to elevated levels of CO_2 that surpass any other period in human history. Elevated levels of CO_2 emissions have wide-ranging implications that provide significant risks to ecosystems, biodiversity, and human welfare.[2,3]

Human-caused emissions have worsened climate change. From 1990 to 2022, global greenhouse gas emissions surged by 61.7%, reaching 53,786 million CO_2-equivalent tons in 2022 from 33,268 million CO_2-equivalent tons in 1990.[4] However, the COVID-19 pandemic caused a 3.7% drop in emissions in 2020 with regard to the previous year, breaking a decade-long trend of increase. Despite this temporary decline, emissions quickly rebounded, hitting 53,786 million CO_2-equivalent tons in 2022, a 2.3% rise from 2019 and a 1.4% increase from 2021, indicating an upward trend.[5] Despite climate change mitigation agreements, CO_2 emissions, the primary contributors to global greenhouse gas emissions, continue to increase worldwide. In 2022, global greenhouse gas emissions still predominantly comprised CO_2, stemming from fossil fuel combustion (71.6%). Since 1900, there has been a notable surge in global carbon emissions from fossil fuels.[6] From 1990 to 2022, there was an increase of over 71% in global CO_2 emissions.[7] The emissions of CO_2 started rising notably from the 1950s, reaching 25.5 billion metric tons by 2000. Between 2000 and 2010, emissions saw a steep increase of 31.1%,[8] reaching a total of 38.5 billion metric tons in 2022.[7]

To reduce CO_2 emissions effectively, the utilization of clean (including renewable and nuclear) energy sources is crucial.[9–11] Transitioning to renewable energy allows us to reduce reliance on fossil fuels and decrease CO_2 emissions, thereby mitigating the effects of climate change.[12,13] Renewable energy has a lower environmental footprint compared to conventional power plants, potentially safeguarding natural ecosystems and biodiversity.[14]

Various regulatory measures (e.g. environmental taxes; setting emission reduction targets, emission trading systems, implementing carbon pricing, and promoting energy efficiency) have been applied to ensure the decline in CO_2 emissions.[15–17] In stricter environmental policies, tools to reduce greenhouse gas emissions are often included.[18] These policies incentivize both industries to adopt cleaner technologies and methods, thus reducing emissions. Therefore, the stringency of environmental policies relates to the level of enforcement and compliance required by environmental regulations and standards. The environmental policy stringency (EPS) index functions as a nation-specific and globally comparable gauge, evaluating the rigor of environmental policies. Stringency refers to the degree to which environmental policies impose implicit or explicit costs on activities that pollute or harm the environment.

The global trend of CO_2 emissions has been on the rise primarily due to increased emissions from China and other emerging countries. In 2022, the five largest CO_2 emitters globally were China (32.88%), the United States (12.60%), the EU-27 (7.28%), India (6.99%), and Russia (4.96%). Three out of the five largest emitters seem to be BRICS countries. Brazil (1.21%) and South Africa (1.05%) ranked 16th and 18th among the largest greenhouse gas emitters, respectively. Together, BRICS countries constituted 47.1% of the global CO_2 emissions. Among these countries, only India witnessed a 6.5% increase in emissions compared to 2021. Conversely, the remaining four countries saw a reduction in their emissions in 2022, with Brazil recording the largest decrease at −7.3%.[7] The tendency of CO_2 emissions for BRICS countries is given in Figure 1.

Between 1990 and 2022, the sharpest increase occurred in China and India. In the 1990s, Russia experienced a decline in CO_2 emissions, which can be attributed to the closure of numerous industrial sectors following the Soviet Union collapse. In Brazil and South Africa, CO_2 emissions have increased at a slower rate compared to other countries. Nevertheless, it can be argued that despite efforts, BRICS nations still exhibit significant overall CO_2 emissions. Thus, assessing the effectiveness of environmental measures and energy transition becomes imperative. Notably, there's a dearth of literature focusing on the BRICS countries regarding the effects of EPS and energy transition on CO_2 emissions.

Addressing this research gap, this study tries to address several key research questions as follows: (i) What is the efficacy of EPS in reducing CO_2 emissions in BRICS?; (ii) What is the role of energy transition in curbing CO_2 emissions in BRICS?; (iii) What is the effect of gross

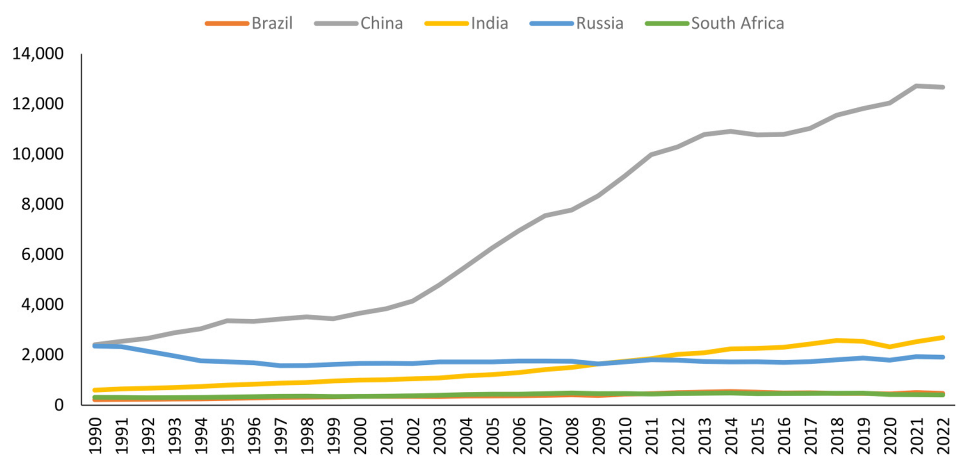

Figure 1. CO_2 emissions of BRICS countries. Source: EDGAR.[7] *Note: The unit is a million tons.*

domestic product (GDP) on CO_2 emissions in BRICS?; (iv) Do the effects of EPS, energy transition, and income differ across times, frequencies, and countries? Thus, this study aims to comprehensively analyze the effect of the aforementioned factors on CO_2 emissions through employing a novel wavelet local multiple correlation (WLMC) approach in BRICS countries, which are significant contributors to global CO_2 emissions as well as having an approximately 26% share in global GDP and 41% share in global population.[19] All of the facts mentioned above render BRICS economies a unique case for this investigation.

By searching for answers to the specified research questions above, the study makes contributions to the literature by expanding knowledge in various ways. First, this research analyzes the effect of EPS on CO_2 emissions in BRICS countries. This is important because they are responsible for nearly half (47.1%) of global CO_2 emissions as well as they have implemented various environmental policies to decarbonize economies to protect the environment. Second, by differentiating from most current studies, this research considers energy transition index (ETI) as a comprehensive indicator for clean energy transition. ETI offers a comprehensive measure of energy transition, taking into account factors, such as energy usage, and availability, sustainability, and the renewable aspects of energy sources. Hence, rather than relying on the proportion of renewable energy use in the total energy, which is the primary focus in previous studies, the study uses a novel indicator to proxy the energy transition efforts. Third, this research offers a comprehensive time series analysis under the time and frequency-based diverging scheme so that the effects of the variables considered on CO_2 emissions can be examined across different times and frequencies in both bivariate and multivariate cases. Consequently, the study integrates thorough theoretical and econometric elements to provide the aforementioned contributions to the literature.

The study goes with a literature review in the second section, methods in the third section, empirical results in the fourth section, and a conclusion in the last section.

Literature review

Literature on the environmental policy stringency

EPS refers to the rigor and enforcement level of laws and regulations designed to protect the environment. Numerous studies have been conducted on a group of countries with panel data methods (e.g. CS-ARDL) to evaluate the role of the EPS in environmental protection. The vast majority of these studies have demonstrated that stringent policies significantly influence the shift toward renewable energy sources, enhance environmental performance, and ultimately reduce overall CO_2 emissions.

Ahmed and Ahmed[20] examine the influence of the EPS on CO_2 emissions and find that EPS can significantly reduce emission in China. Albulescu et al.[15] further investigate the causality between the EPS and CO_2 emissions in 32 Organisation for Economic Co-operation and Development (OECD) countries for the same period and report the results consistent with Wang et al.,[21] reinforcing the importance of stringent environmental regulations. Furthermore, Frohm et al.[16] explore the effect of the EPS on CO_2 emissions within 30 OECD countries and more than 50 sectors, concluding that a 1% increase in EPS results in a 4% decrease in CO_2 emissions after 2 years.

This body of literature highlights the critical role of stringent environmental policies in mitigating climate change. However, some studies have yielded contradictory and mixed conclusions. Chu and Tran[22] examine 27 OECD nations and conclude that the EPS reduces the ecological footprint, though the effect is asymmetric. Conversely, Li et al.[23] analyze 21 OECD countries and find that EPS had a contractionary influence on CO_2 emissions.

The pursuit of a low-carbon environment has also become a priority for emerging economies (e.g. BRICS countries). These countries face the dual challenge of fostering economic growth while mitigating environmental degradation. Sezgin et al.[24] study the EPS on CO_2 emissions in G7 and BRICS countries and find that stringent policies causally reduce CO_2 emissions. These results are supported by Udeagha and Ngepah,[25] who identify a long-term effect of the EPS on CO_2 emissions in BRICS countries from 1960 to 2020.

Literature on the energy transition

Energy transition is a priority for many countries. Reducing the use of traditional energy sources, such as fossil fuels, in favor of renewable (carbon-free) resources is essential for sustainable development. This transition helps reduce pollution, increase energy security, and promote long-term economic growth and development. Numerous studies support the positive environmental effect of increased renewables as a proxy for energy transition.

Recent studies by Danish et al.,[26] Akram et al.,[27] Shahnazi and Shabani,[28] and Makhdum et al.,[29] among others, have concluded that increased renewable energy consumption reduces ecological degradation. Specifically, Khoshnevis Yazdi and Ghorchi Beygi[30] examine the long-term effect of renewable energy on CO_2 emissions from 1992 to 2014 in 13 European Union countries, revealing a significant decreasing effect.

Studies by Saidi and Omri[31] for 15 OECD countries, Leitão and Lorente[32] for EU-28 countries, Balsalobre-Lorente et al.[33] for 5 European countries, and Okumus et al.[34] for G7 countries, Ali and Kirikkaleli[35] for Italy, and Mukhtarov[36] for Canada, have also concluded that renewable energy reduces CO_2 emissions.

In developing countries, similar trends have been observed. Dong et al.[37] demonstrate the negative and significant effect of renewable energy on CO_2 emissions in 120 economies from 1995 to 2015. Similarly, Zoundi[38] find this effect in 25 African countries. Danish et al.[39] and Waheed et al.[40] identify this trend for Pakistan, Kahia et al.[41] and Charfeddine et al.[42] for Middle East and North Africa (MENA) countries, Cheng et al.[43] for BRICS countries, Akram et al.[27] for 66 developing countries, Hasanov et al.[44] for BRICS countries, and Mukhtarov et al.[45] for Azerbaijan. In the case of Türkiye, Shan et al.,[46] and Mukhtarov[47] have reached the same conclusion.

This stream of studies overwhelmingly supports the notion that increasing renewable energy leads to a reduction in CO_2 emissions and highlights the universal benefits of transitioning to renewable energy sources.

Nevertheless, contradictory results have been found. Such that Apergis et al.[48] find an increasing effect of renewable energy on CO_2 emissions for 12 developing and developed countries, and unidirectional causality from renewable energy consumption (REC) to CO_2 emissions, supported by Belaïd and Youssef.[49]

The methodologies employed in these studies vary but consistently reinforce the curbing effect of renewable energy on CO_2 emissions in the vast majority of them. Techniques used vary and these diverse methodological approaches enhance the robustness and validity of the findings across different contexts and periods.

Literature on the income

Several empirical studies have delved into the nexus between GDP growth and environmental indices across various countries and regions, with a particular emphasis on energy transition.

In the case of an individual country, Kassori et al.[50] observe a positive association between GDP growth and renewable energy in the United States. Li et al.[23] emphasize the positive influence of GDP growth on energy transition in Tunisia, particularly through increased investment in renewable energy as a proxy for energy transition. Saadaoui and Chtourou[51] identify GDP growth as a catalyst for energy transition in Tunisia, highlighting the contextual factors pivotal in shaping the relationship between income and environmental sustainability. Using a machine learning algorithm and a nonparametric regression approach, Pata et al.[52] report that GDP is one of the important factors for energy transition in the United States.

Using panel data approaches, Murshed and Tanha[53] find that GDP growth positively correlates with the share of renewable energy in South Asian economies. Similarly, a comprehensive analysis by Shahbaz et al.[54] across 72 countries affirms that GDP growth fosters renewable energy use. Using a panel vector autoregression model, Tzeremes et al.[55] focused on the BRICS countries and find that GDP growth, along with CO_2 emissions, plays a significant role in driving energy transition in BRICS countries.

However, contrasting findings are also reported in the literature. In the case of 45 countries, Lin and Omoju[56] conclude that GDP growth reduces energy transition. Song et al.[57] reveal that GDP growth decreases renewable energy use, while CO_2 emissions support the energy transition in China.

Income affects the environment in complex ways, and its effectiveness depends on complementary policies, institutional frameworks, technology, and productivity. According to the EKC (Environmental Kuznets Curve) hypothesis, initially higher GDP might increase environmental effects due to more industrial activity and consumption.[58] However, it also provides the financial capacity for investment in cleaner technologies and sustainable practices. In turn, stringent environmental policies and investment in renewable energy transition encourage the use of clean technologies and sustainable practices, ensuring that economic growth does not harm the environment.

Evaluation of the literature

The interrelation of environmental policy stringency, energy transition, and income has not been specifically studied in the mainstream of research. The effect of each of these factors individually on environmental protection varies depending on countries and regions' specifics, time intervals, research methodologies, and control variables used in estimations. So, this study employs the WLMC approach for studying this relationship in ensuring a low-carbon environment in BRICS countries. This method offers several distinct advantages over traditional methods used in previous studies by overcoming methodological limitations. This methodological innovation not only enhances the credibility and robustness of our findings but also contributes to advancing the methodological frontier in the field of environmental economics and policy analysis.

Methods

Data and variables

In investigating the effect of EPS, ETI, and GDP on the environment, this research uses CO_2 emissions as the proxy of the environment to focus on the decarbonization perspective.[59,60] In doing so, the study collects data on CO_2 emissions from EI (Energy Institute).[61] Data on EPS, ETI, and GDP is collected from OECD,[62] UNCTAD,[63] and WB (World Bank)[19] sources, in order. Table 1 summarizes the details of the variables.

This study uses data for the countries from 2000 to 2020 because data on ETI starts from 2000 and data on EPS ends in 2020. Following the collection of annual data, the study applies the transform of annual data into quarterly data and then performs logarithm on the quarterly transformed

Table 1. Variables.

Symbol	Definition	Unit	Data source
$lnCO_2$	CO_2 emissions*	Million tons	EI [61]
lnEPS	Environmental policy stringency**	Index	OECD [62]
lnETI	Energy transition**	Index	UNCTAD [63]
lnGDP	Gross domestic product**	Constant USD	WB [19]

Notes: * and ** denote dependent and independent variables, in order.

dataset to use elasticities in the empirical analysis. Hence, the overall data is between 2000/Q1 and 2020/Q4 for the variables across the countries.

Empirical methodology

To uncover the effect of EPS, ETI, and GDP on CO_2 emissions, the study follows the empirical procedure as shown in Figure 2.

The study initially examines the basic characteristics. In this context, the study examines firstly descriptive statistics and analyzes secondly correlations. Thirdly, the study uncovers the stationarity status by using the PP (Phillips-Perron) test.[64] Fourthly, the study examines the nonlinearity status by applying the BDS (Broock, Scheinkman, Dechert, and LeBaron) test.[65] Following the completion of the examination of the fundamental characteristics, the study applies the WLMC approach to investigate the bi-variate and four-variate cases nexus of EPS, ETI, and GDP with CO_2 emissions.[66]

Equations (1) to (3) are used to investigate the nexus between variables in bi-variate case:

$$\text{lnCO}_2 = \text{f (lnEPS)} \tag{1}$$

$$\text{lnCO}_2 = \text{f (lnETI)} \tag{2}$$

$$\text{lnCO}_2 = \text{f (lnGDP)} \tag{3}$$

Equation (4) is considered to uncover the nexus between variables in the four-variate case:

$$\text{lnCO}_2 = \text{f (lnEPS, lnETI, lnGDP)} \tag{4}$$

WLMC approach

The WLMC approach enables multivariate interaction analysis.[66] With this approach, the association between two variables can be investigated by considering the effects of additional variables at various time and frequency intervals. In addition, the WLMC approach provides visual evidence of the dominant explanatory variable. The first stage of the WLMC approach is shown in equation (5).

$$W_w = \sum_t \delta(t - w)[E_w(R_{-i,t})r_{it}]^2 \tag{5}$$

where R shows a multivariate time series factor, t denotes the time (12,3…T), and $\delta(r)$ illustrates a moving average function of time. In the second stage, the local determinant coefficients can be expressed as in equation (6):

$$Z_r^2 = 1 - \frac{ZwRR_r}{TWRR_r} \tag{6}$$

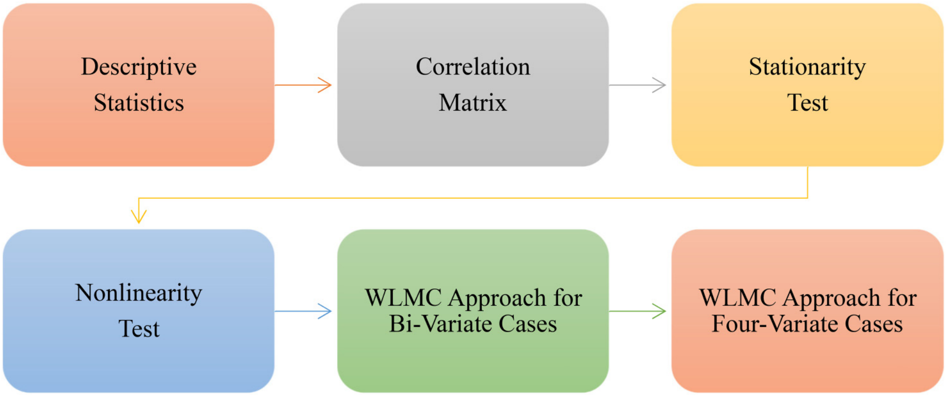

Figure 2. Empirical procedure.

where $ZwRR_r$ shows residual SS (sum of squares), and $TWRR_r$ denotes overall SS. In the third stage, the wavelet coefficients for the k ($k = 1,\ldots,k$) scale are estimated as $U_{kt} = (U_{1jt\ldots,} U_{nkt})$. In the fourth stage, WLMC estimation $\delta R(\delta K)$ is made as in equation (7) by calculating the square root of the regression coefficient of determination.

$$\hat{\delta} W_r(\theta_k) = \sqrt{Z_r^2}, k = 1, \ldots, k \qquad r = 1, \ldots, T \tag{7}$$

In equation (7), for each wavelet scale ((θ_k), WLMC ($\hat{\delta} W_r(\theta_k)$) is estimated as the square root of the regression coefficient of determination. In the final stage, following Polanco-Martínez et al.,[66] a consistent WLMC estimator is calculated as in equation (8).

$$\hat{\delta} W_r(\theta_k) = corr\left((\delta(t-r)^{\frac{1}{2}} W_{ik}, \sqrt{Z_r^2}, (\delta(t-r)^{\frac{1}{2}} \hat{W}_{ik} \right) \tag{8}$$

where W_{ik} is selected to maximize $\hat{\delta} W_r(\theta_k)$ and $\hat{W}_{ik}$ the vector of fitted variables.

Table 2 presents the axis information for WLMC graphs.

Empirical results

Preliminary statistics

Before going further in the empirical analysis by performing the main approach, the study analyzes the preliminary statistics. In this context, the descriptive statistics of the variables, which are reported in Table 3, are first examined.

In Brazil, Russia, China, and South Africa, lnGDP has the highest mean and maximum values. Also, lnEPS has the highest variations among all variables followed by lnGDP, $lnCO_2$, and lnETI, in order. Besides, all variables excluding lnETI have a non-normal distribution in Brazil, whereas only $lnCO_2$ has a normal distribution in Russia, and all variables are normally distributed in China and South Africa at a 90% significance level. In India, lnGDP has the highest mean and maximum values. Also, lnGDP has the highest variations among all variables followed by lnEPS, $lnCO_2$, and lnETI, in order. Moreover, all variables excluding lnEPS have a non-normal distribution.

Table 2. Time and frequency schedule for WLMC graphs.

Panel	Number of observation	Exact date
Panel A: Time schedule	1st	2000/Q1
	20th	2004/Q4
	40th	2009/Q4
	60th	2014/Q4
	80th	2019/Q4
	Last	2020/Q4
	Interval	**Term**
Panel B: Frequency schedule	2–4	Low frequency
	4–8	Medium frequency
	8–16	High frequency

WLMC: wavelet local multiple correlation.

After examination of the descriptive statistics, Table 4 presents the correlations between the variables across the countries.

In all countries, the explanatory variables (i.e. lnEPS, lnETI, and lnGDP) have a positive correlation with $\ln CO_2$ based on the mean point. When each country is considered, the power of correlation between the variables differentiates. In Brazil, Russia, and India, $\ln CO_2$ has a relatively low positive correlation with lnEPS and has a high positive correlation with both lnETI and lnGDP. In China, $\ln CO_2$ has a low positive correlation with lnGDP and has a high positive correlation with both lnEPS and lnETI. In South Africa, $\ln CO_2$ has a low positive correlation with lnETI and has a high positive correlation with both lnEPS and lnGDP.

Following the examination of correlations, Table 5 demonstrates stationarity test results.

Based on the PP test, all variables have a unit root at the level, whereas they are stationary at the first differences in Brazil, India, and South Africa. In Russia, all variables are stationary at the first differences, whereas lnGDP is stationary at the level. In China, lnEPS is stationary at the first differences, whereas the remaining variables are stationary at the level.

Moreover, the results of the nonlinearity examination are reported in Table 6.

According to the BDS test results, all variables have a nonlinear property across all dimensions in all countries. Overall, there are high deviations across variables, variables have a mainly non-normal distribution; there are generally strong correlations between the variables; variables are mostly stationary at $I(1)$, whereas some of them are stationary at $I(0)$, and all variables have a nonlinear structure. In line with these defined properties of the variables, the usage of nonlinear approaches can be more suitable for detailed empirical investigation. For this purpose, in line with the data characteristics, the study performs the novel WLMC approach to make a comprehensive econometric analysis to consider possible changing nexus between the variables across times and frequencies as in line with the contemporary literature that uses the same econometric approach.[67]

WLMC results

WLMC results for bi-variate cases. In the context of the empirical investigation, the study first examines the bi-variate cases between the variable pairs. So, Figure 3 presents the bi-variate effect of lnEPS on $\ln CO_2$ in the countries.

In Brazil, there is negative co-movement between lnEPS and $\ln CO_2$ at low and high frequencies between 2000/Q1 and 2020/Q4, where there is a statistically significant effect. However, at medium

Table 3. Descriptive statistics.

Country	Variable	Mean	Median	Maximum	Minimum	Standard deviation	Skewness	Kurtosis	Jarque-Bera	JB Probability
Brazil	lnCO_2	4.60	4.61	4.85	4.36	0.15	0.01	1.65	6.40	0.0409
	lnEPS	−2.17	−1.95	−1.46	−3.22	0.61	−0.40	1.57	9.47	0.0088
	lnETI	2.56	2.56	2.60	2.51	0.02	−0.08	2.03	3.36	0.1862
	lnGDP	26.70	26.78	26.87	26.41	0.16	−0.58	1.79	9.92	0.0070
Russia	lnCO_2	5.94	5.94	5.98	5.86	0.03	−0.28	2.08	4.08	0.1302
	lnEPS	−1.60	−1.79	−1.22	−2.04	0.28	0.39	1.37	11.43	0.0033
	lnETI	2.85	2.86	2.89	2.81	0.02	−0.28	1.89	5.43	0.0662
	lnGDP	26.42	26.50	26.63	25.98	0.20	−0.93	2.47	13.01	0.0015
India	lnCO_2	5.98	6.02	6.41	5.48	0.32	−0.21	1.63	7.25	0.0267
	lnEPS	−0.86	−0.86	−0.32	−1.50	0.33	−0.19	2.39	1.81	0.4041
	lnETI	2.20	2.21	2.47	1.84	0.20	−0.23	1.76	6.10	0.0473
	lnGDP	26.65	26.67	27.24	26.00	0.39	−0.07	1.74	5.63	0.0599
China	lnCO_2	7.48	7.62	7.84	6.72	0.35	−1.02	2.66	14.85	0.0006
	lnEPS	−1.25	−1.14	−0.21	−2.95	0.90	−0.47	1.90	7.32	0.0257
	lnETI	2.72	2.75	2.83	2.55	0.09	−0.62	2.06	8.45	0.0146
	lnGDP	28.19	28.27	28.93	27.24	0.54	−0.26	1.75	6.44	0.0400
South Africa	lnCO_2	4.70	4.74	4.79	4.51	0.08	−1.15	3.00	18.58	0.0001
	lnEPS	−1.92	−1.54	−0.75	−3.17	0.67	−0.22	1.78	5.90	0.0522
	lnETI	2.68	2.68	2.71	2.60	0.03	−1.18	3.85	22.06	0.0000
	lnGDP	25.04	25.08	25.23	24.73	0.16	−0.65	2.05	9.08	0.0107

EPS: environmental policy stringency; ETI: energy transition index; GDP: gross domestic product.

Table 4. Correlation matrix.

Country	Variable	$lnCO_2$	lnEPS	lnETI	lnGDP
Brazil	$lnCO_2$	1.00			
	lnEPS	0.22	1.00		
	lnETI	0.97	0.09	1.00	
	lnGDP	0.95	0.16	0.94	1.00
Russia	$lnCO_2$	1.00			
	lnEPS	0.38	1.00		
	lnETI	0.65	0.75	1.00	
	lnGDP	0.65	0.73	0.95	1.00
India	$lnCO_2$	1.00			
	lnEPS	0.94	1.00		
	lnETI	1.00	0.96	1.00	
	lnGDP	0.99	0.97	0.99	1.00
China	$lnCO_2$	1.00			
	lnEPS	0.96	1.00		
	lnETI	0.98	0.98	1.00	
	lnGDP	0.95	0.97	0.99	1.00
South Africa	$lnCO_2$	1.00			
	lnEPS	0.77	1.00		
	lnETI	0.71	0.56	1.00	
	lnGDP	0.88	0.81	0.79	1.00

EPS: environmental policy stringency; ETI: energy transition index; GDP: gross domestic product.

frequencies, the effect of lnEPS on $lnCO_2$ is positive (i.e. insignificant to decline CO_2 emissions around 2000 and between 2008 and 2010, whereas it has a curbing effect between 2013 and 2020). Hence, there is mainly a negative (declining) effect of lnEPS on $lnCO_2$, which is consistent with the studies of Stevens[68] on Brazil, Udeagha and Muchapondwa[69] on BRICS panel, Arjun and Mishra[70] on BRICS-T panel, and Kartal et al.[71] on EU-5 countries' some sectors.

In Russia, lnEPS has a mixed nexus with $lnCO_2$. Specifically, lnEPS has a positive nexus with $lnCO_2$ across all frequencies between 2000/Q1 and 2004/Q4. Similarly, there is a positive nexus around 2017/Q2 at low frequency and between 2017/Q2 and 2020/Q4 at medium frequency. These findings imply the inefficiency of lnEPS, which is consistent with the study of Mahalik et al.[72] on the BRICS panel. On the other hand, lnEPS has a declining effect on $lnCO_2$ between 2011/Q2 and 2014/Q2 at medium frequency, which is compatible with the findings of Udeagha and Muchapondwa[69] on the BRICS panel.

In India, lnEPS has also mixed co-movement with $lnCO_2$. In detail, lnEPS has a mostly positive co-movement with $lnCO_2$ at low and medium frequencies around 2004/Q4 as well as between 2009/Q4 and 2017/Q2. Also, there is a positive co-movement around 2004/Q4 and from 2009/Q4 through 2020/Q4 at medium frequency and it is the same around 2017/Q2 at high frequency. It is compatible with the study of Mahalik et al.[72] on the BRICS panel and Kartal et al.[71] on EU-5 countries' sectors. On the other hand, lnEPS has a negative co-movement with $lnCO_2$ around 2020/Q4 at low frequency, around 2000/Q1 at medium frequency, and between 2000/Q1 and 2004/Q4 as well as from 2014/Q4 to 2020/Q4 at high frequency, which is in line with the findings of Udeagha and Muchapondwa[69] on BRICS panel.

In China, although there is mixed effect of lnEPS on $lnCO_2$, it is mainly a negative one. At low, medium, and high frequencies, lnEPS has a highly curbing effect across all frequencies and times

Table 5. PP stationarity test results.

Country	Variable	I(0)	I(1)	Decision
Brazil	$\ln CO_2$	0.4889	0.0008	I(1)
	lnEPS	0.4841	0.0002	I(1)
	lnETI	0.2084	0.0024	I(1)
	lnGDP	0.2496	0.0244	I(1)
Russia	$\ln CO_2$	0.2001	0.0012	I(1)
	lnEPS	0.7007	0.0000	I(1)
	lnETI	0.6242	0.0001	I(1)
	lnGDP	0.0285		I(0)
India	$\ln CO_2$	0.4983	0.0001	I(1)
	lnEPS	0.8324	0.0001	I(1)
	lnETI	0.8642	0.0000	I(1)
	lnGDP	0.4613	0.0000	I(1)
China	$\ln CO_2$	0.0171		I(0)
	lnEPS	0.5788	0.0001	I(1)
	lnETI	0.0225		I(0)
	lnGDP	0.0110		I(0)
South Africa	$\ln CO_2$	0.2082	0.0009	I(1)
	lnEPS	0.5522	0.0000	I(1)
	lnETI	0.3488	0.0002	I(1)
	lnGDP	0.0778	0.0001	I(1)

Notes: The decision is based on a 5% significance level.
EPS: environmental policy stringency; ETI: energy transition index; GDP: gross domestic product; PP: Phillips-Perron.

except for 2014/Q4 to 2020/Q4 at low and medium frequencies and 2000/Q1 to 2002/Q2 at high frequency. Hence, lnEPS is mainly beneficial for the Chinese case as it the compatible with the study of Udeagha and Muchapondwa[69] on the BRICS panel, and Arjun and Mishra[70] on BRICS-T panel.

In South Africa, lnEPS has a mixed co-movement with $\ln CO_2$. In specific, lnEPS has a mostly positive co-movement with $\ln CO_2$ at low and medium frequencies before 2007/Q2. Similarly, there is a positive co-movement from 2012/Q4 through 2020/Q4 at high frequency. This determination is similar to the study of Mahalik et al.[72] on the BRICS panel and Kartal et al.[71] on EU-5 countries' sectors. However, lnEPS has a negative co-movement with $\ln CO_2$ around 2009/Q4 and from 2017/Q2 to 2020/Q4 at low and medium frequency as well as between 2000/Q1 and 2009/Q4 at high frequency, which is similar to the findings of Udeagha and Muchapondwa[69] on BRICS panel.

In summary, EPS is highly beneficial to combat CO_2 emissions in Brazil, whereas there are mixed effects for the remaining BRICS countries.

Also, Figure 4 demonstrates the bi-variate effect of lnETI on $\ln CO_2$ in the countries.

In Brazil, Russia, and China, lnETI has a positive effect on $\ln CO_2$ across all times and frequencies, while the power of increasing effect varies, the effect certainly reveals the inefficiency of energy transition in curbing CO_2 emissions in these countries. This result is consistent with Mahmood[73] on low and middle-income countries as well as upper-middle-income countries and Tiwari et al.[74] on emerging countries.

In India, lnETI has a positive effect on $\ln CO_2$ at low and medium frequencies. Across all times. However, the effect becomes a decreasing one at a high frequency between 2017/Q2

Table 6. BDS nonlinearity test result.

Country	Variable	DM2	DM3	DM4	DM5	DM6	Decision
Brazil	$lnCO_2$	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnEPS	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnETI	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnGDP	0.0000	0.0000	0.0000	0.0000	0.0000	NL
Russia	$lnCO_2$	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnEPS	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnETI	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnGDP	0.0000	0.0000	0.0000	0.0000	0.0000	NL
India	$lnCO_2$	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnEPS	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnETI	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnGDP	0.0000	0.0000	0.0000	0.0000	0.0000	NL
China	$lnCO_2$	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnEPS	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnETI	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnGDP	0.0000	0.0000	0.0000	0.0000	0.0000	NL
South Africa	$lnCO_2$	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnEPS	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnETI	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	lnGDP	0.0000	0.0000	0.0000	0.0000	0.0000	NL

Notes: DM and NL denote dimensions and nonlinear, in order.
EPS: environmental policy stringency; ETI: energy transition index; GDP: gross domestic product.

and 2020/Q4. Conversely, in the South Africa case, lnETI has a decreasing effect on $lnCO_2$ at low and medium frequencies from 2000/Q1 through 2016/Q1. However, after this date, the effect becomes an increasing one at low and medium frequencies as well as across all times at high frequencies. So, the declining effect of ETI on CO_2 emissions is compatible with Koengkan and Fuinhas[75] on LAC countries, Lau et al.[76] on 36 OECD countries, and Ahmad et al.[77] on 26 EU countries.

To sum up, ETI is partially helpful in curbing CO_2 emissions in India (South Africa) at medium and high (low and medium) frequencies, whereas it is not effective in the remaining countries.

Moreover, Figure 5 shows the bi-variate effect of lnGDP on $lnCO_2$ in the countries.

In Brazil and China, lnGDP has an increasing effect on $lnCO_2$ across all times and frequencies while the power of increasing effect differentiates. This determination is compatible with Lau et al.[76] on 36 OECD countries.

In Russia, lnGDP has an almost stimulating effect on $lnCO_2$ emissions across all times and frequencies excluding that at higher frequency between 2000/Q1 and 2004/Q4. In India and South Africa cases, lnGDP has a mixed (i.e. negative and positive) across low and medium frequencies while varying across times. Moreover, lnGDP has a decreasing (increasing) effect on $lnCO_2$ at higher frequency in India (South Africa). The increasing effect of lnGDP on $lnCO_2$ emissions is consistent with Lau et al.[76] on 36 OECD countries, whereas the decreasing effect is compatible with Pata et al.[52] on the Germany case.

In summary, GDP is relatively beneficial to curb CO_2 emissions in India at high frequencies, whereas this is not the case for the remaining countries.

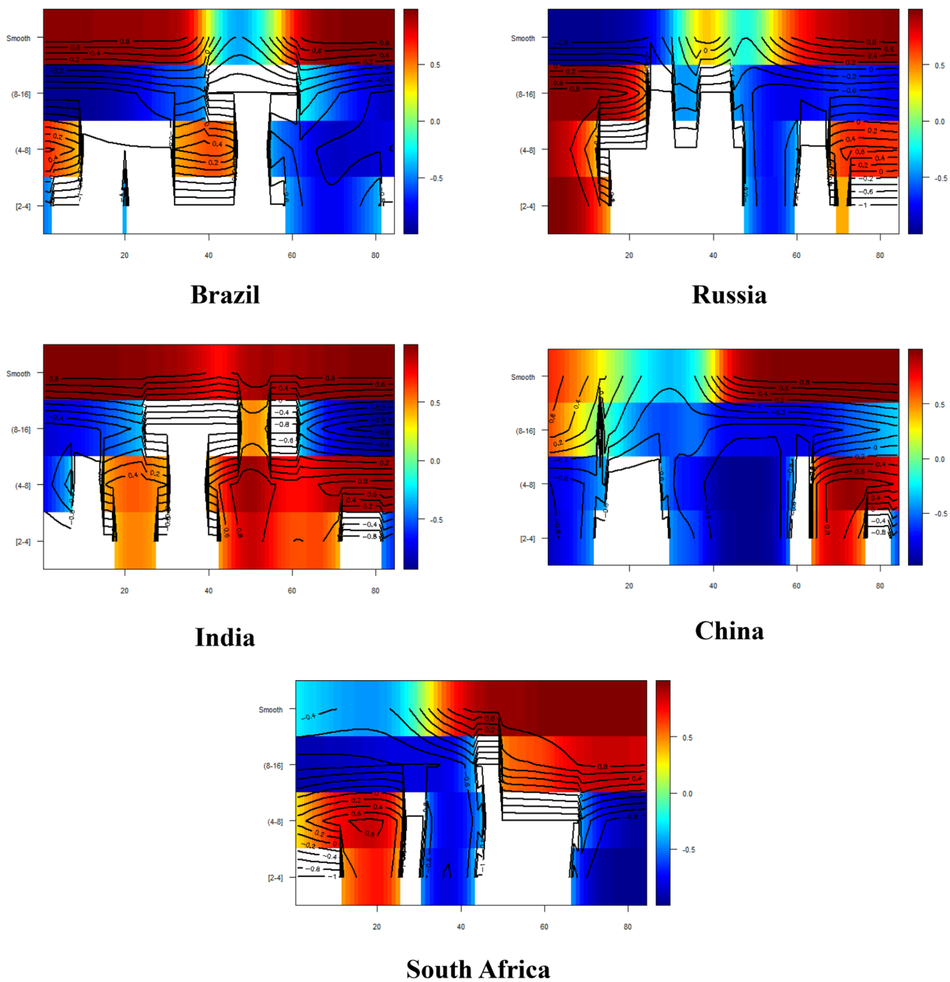

Figure 3. WLMC results for bi-variate cases for lnEPS effect on $lnCO_2$. EPS: environmental policy stringency; WLMC: wavelet local multiple correlation.

WLMC results for four-variate cases. After the examination of bi-variate cases, the study investigates the four-variate cases. So, Figure 6 shows the four-variate effect of the variables on $lnCO_2$ in the countries.

Although the effect of the variables in bi-variate cases differ across times, frequencies, and countries, as Figure 6 demonstrates, the combined effect of lnEPS, lnETI, and lnGDP on $lnCO_2$ emissions in a certain way that causes an increase. When the countries are examined, it is seen that the combined effect is quite high in China and India, whereas it is a bit lower in the remaining countries.

Lastly, the study uncovers the heat map, which is related to the variable importance across times and frequencies. Figure 7 presents the heat map results.

In Brazil, lnGDP has a dominant position concerning lnEPS and lnETI at low frequencies. However, lnETI has a leading role at medium and high frequencies. In Russia, lnETI has a

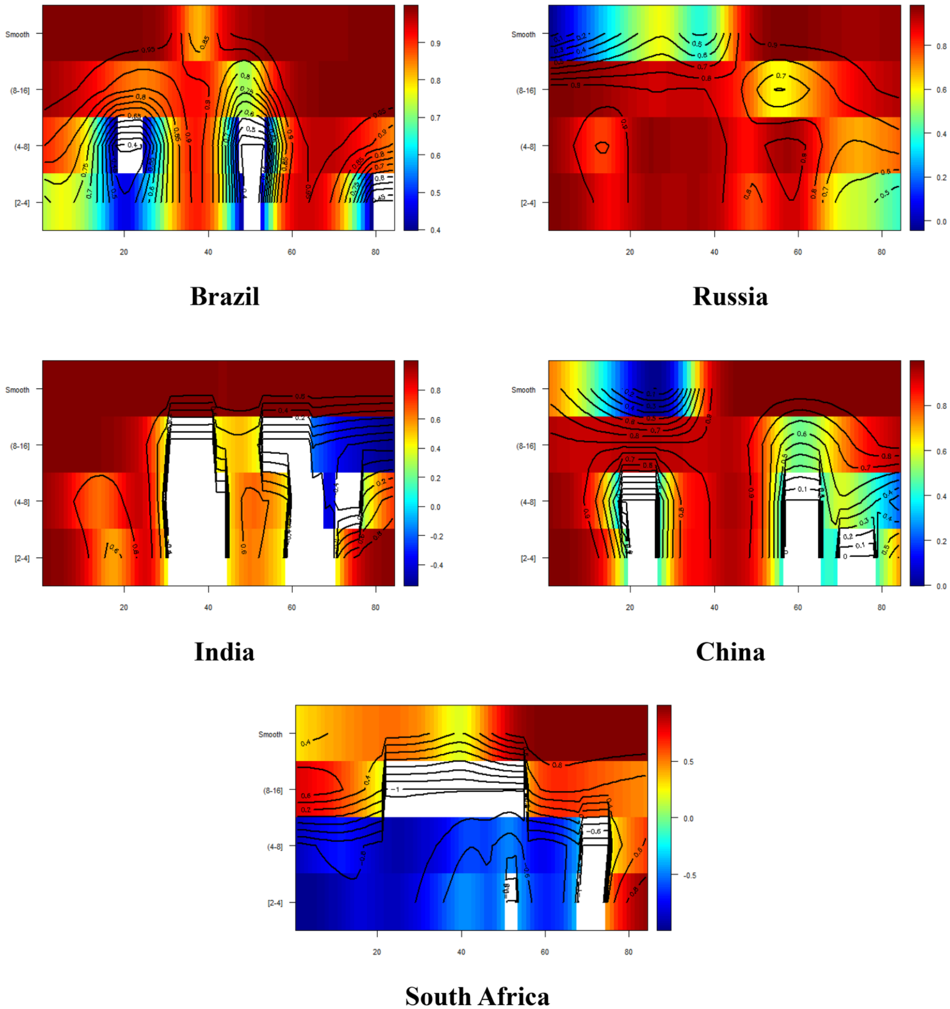

Figure 4. WLMC results for bi-variate cases for lnETI effect on $lnCO_2$. ETI: energy transition index; WLMC: wavelet local multiple correlation.

dominant role across frequencies excluding that lnGDP is the pioneering one at high frequencies. In India, lnETI has a leading role at low and high frequencies, whereas lnGDP is the leading one at medium frequencies. In China, lnETI, lnEPS, and lnGDP are the leading at low, medium, and high frequencies, in order. In South Africa, lnEPS is the leading one at low and medium frequencies, whereas lnETI is the leading one at higher frequencies.

To sum up, ETI is the most dominant factor across the countries except for South Africa, where EPS is the leading one.

Summary of results

Table 7 presents a summary of empirical results.

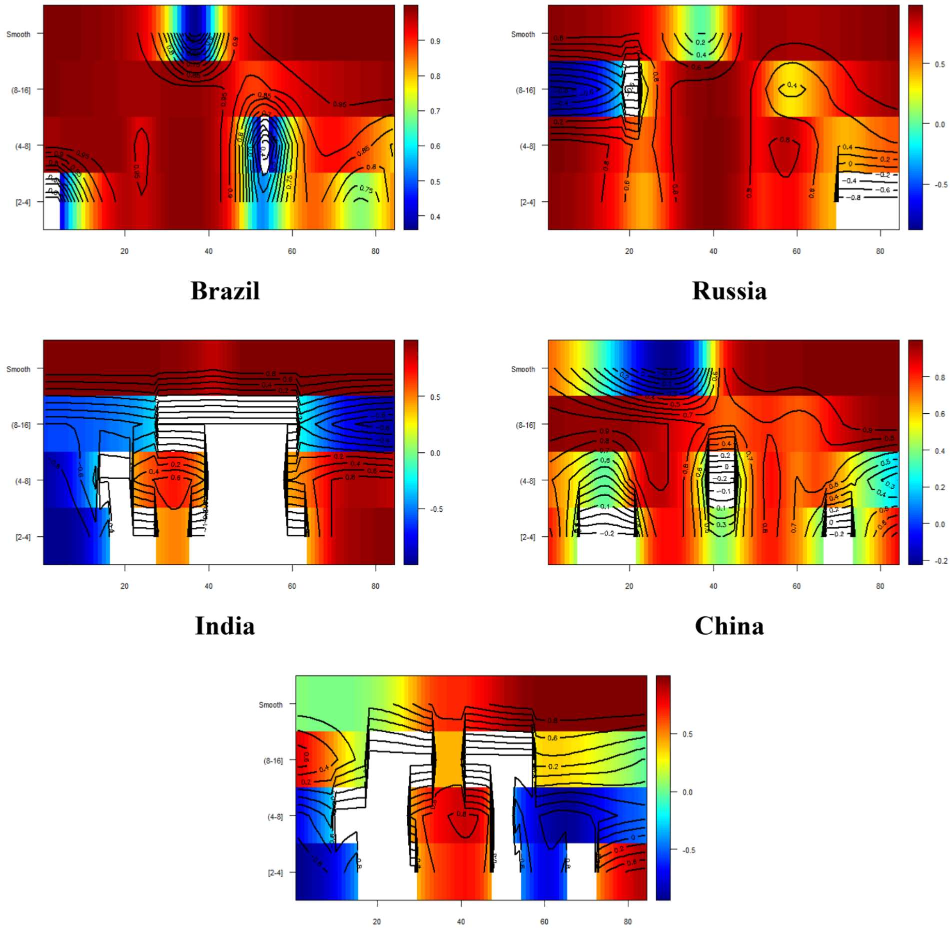

Figure 5. WLMC results for bi-variate cases for lnGDP effect on $lnCO_2$. GDP: gross domestic product; WLMC: wavelet local multiple correlation.

Conclusion, policy suggestions, and future research

Conclusion and discussion

BRICS countries are those, which have been growing rapidly and causing a high amount of CO_2 emissions. For this reason, curbing CO_2 emissions in these countries has a critical importance in achieving global SDGs. Compatible with this reality this research examines the effect of some critical factors (i.e., EPS, ETI, and GDP) on CO_2 emissions in BRICS countries by performing a novel WLMC approach.

The results of the study suggest that, in bivariate cases, EPS contributes to the reduction of CO_2 emissions in Brazil, while GDP growth minimizes environmental degradation in India at high frequencies. However, multivariate cases show that EPS, ETI, and GDP have an increasing effect on CO_2 emissions in all BRICS countries. The dominance levels of the variables on CO_2 are listed as

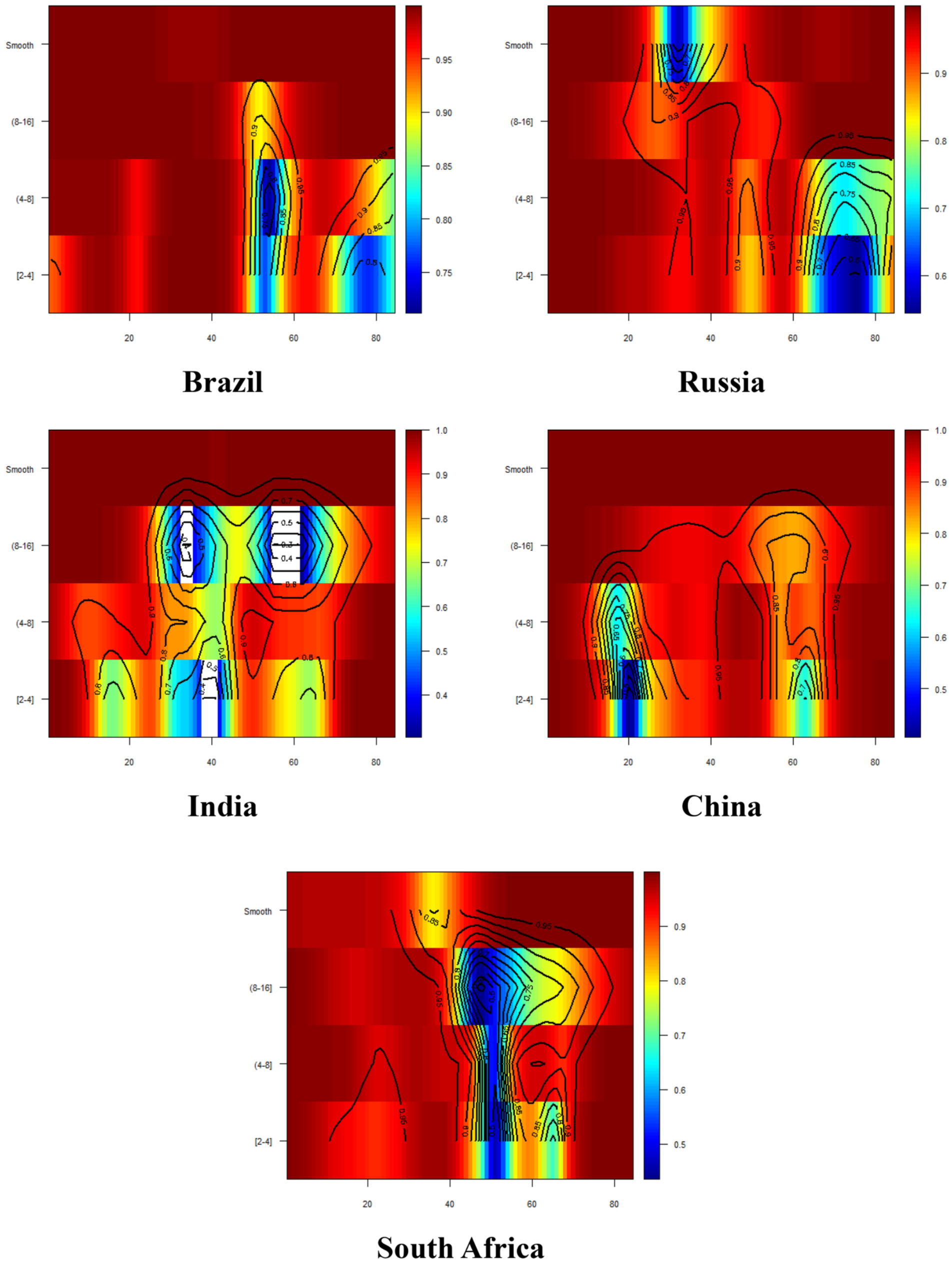

Figure 6. WLMC results for four-variate cases. WLMC: wavelet local multiple correlation.

GDP, ETI, and EPS. The effect of EPS is quite small compared to GDP and ETI in all countries, except in South Africa.

The findings from the WLMC approach highlight the varying effects of EPS, ETI, and GDP on CO_2 emissions in BRICS countries. Hence, policymakers should care about the specialized

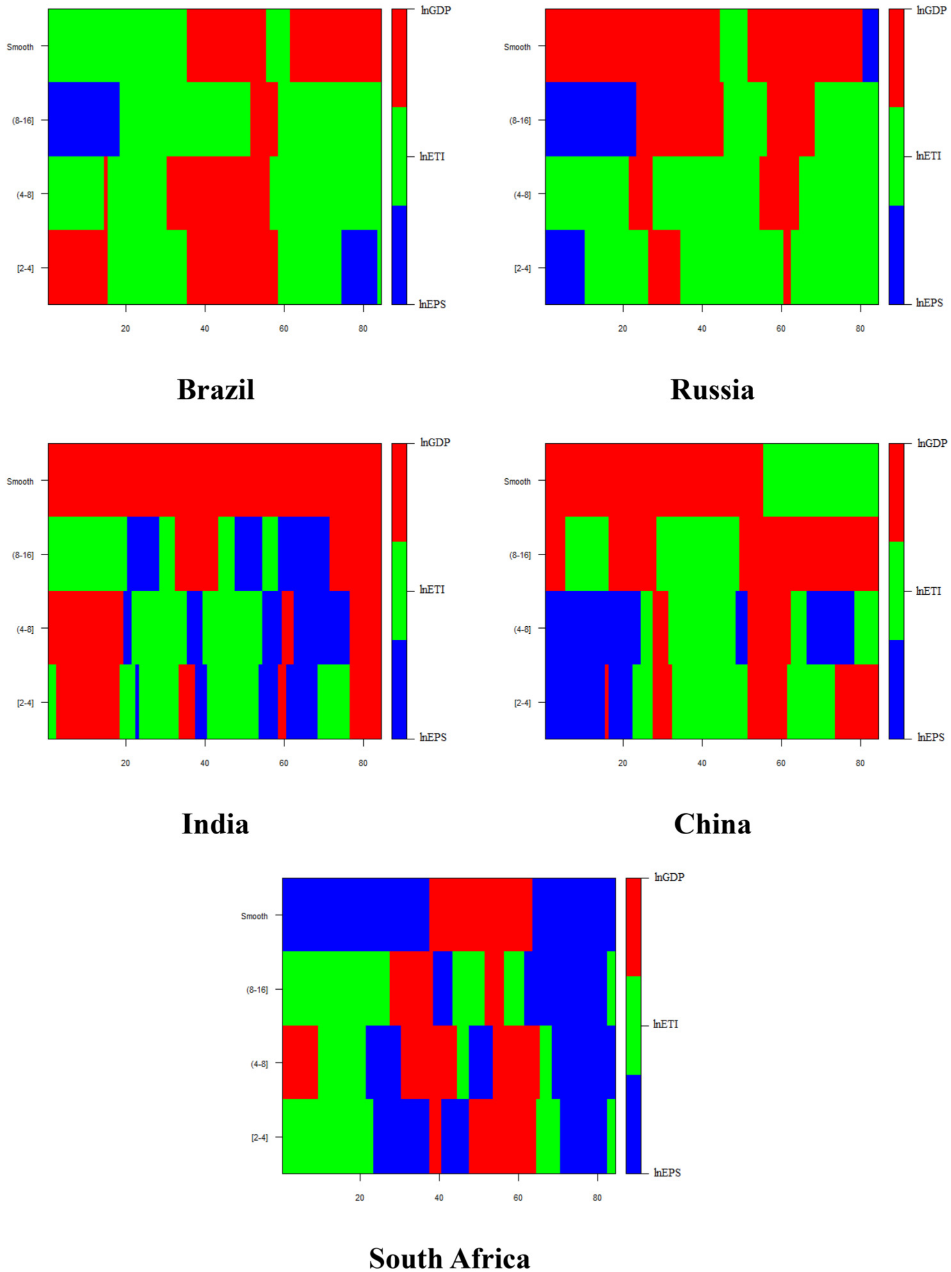

Figure 7. WLMC heat map. WLMC: wavelet local multiple correlation.

policy suggestions by considering own condition of each country. The results obtained are generally in the same direction as the present studies in the literature (e.g. references [70] and [69] for the effect of EPS[74]; for the effect of ETI[52]; for the effect of GDP). On the other hand, new findings of this research extend the knowledge of the concept by considering time, frequency,

Table 7. Summary of the results.

Panel	Variable	Frequency	Brazil	Russia	India	China	South Africa
Panel A:	lnEPS	LF	−	+,−	+,−	+,−	+,−
Bi-variate cases	on $\ln CO_2$	MF	+,−	+,−	+,−	+,−	+,−
		HF	−	+,−	+,−	+,−	+,−
	lnETI	LF	+	+	+	+	+,−
	on $\ln CO_2$	MF	+	+	+,−	+	+,−
		HF	+	+	+,−	+	+
	lnGDP	LF	+	+	+,−	+	+,−
	on $\ln CO_2$	MF	+	+	+,−	+	+,−
		HF	+	+,−	−	+	+
Panel B:	Effect of lnEPS, lnETI, and	LF	+	+	+	+	+
Four-variate	lnGDP on $\ln CO_2$	MF	+	+	+	+	+
cases		HF	+	+	+	+	+
	Heat Map	LF	lnGDP	lnETI	lnETI	lnETI	lnEPS
		MF	lnETI	lnETI	lnGDP	lnEPS	lnEPS
		HF	lnETI	lnGDP	lnETI	lnGDP	lnETI

Notes: LF, MF, and HF denote low-, medium-, and high-frequency, in order. + and − denote the increasing and decreasing effect.
EPS: environmental policy stringency; ETI: energy transition index; GDP: gross domestic product.

and country-based differentiating points of view. In this way, the results enable researchers to provide various policy endeavors for shaping environmental policies and the energy transition of the BRICS countries.

Policy suggestions

Similar to most countries, BRICS countries have committed to curb CO_2 emissions. Although they have such a commitment, nevertheless, there has not been a sharp decrease, instead, their emissions have continued to rise rapidly, especially in the cases of India and China.

Within the context of the reduction of CO_2 emissions, ensuring a clean energy transition is highly important for all countries including BRICS ones. However, BRICS countries have still had an energy mix that they are highly dependent on fossil fuel energy use. The share of fossil fuels in total energy is South Africa (94%), India (88%), Russia (86%), China (81%), and Brazil (50%) in 2022.[78] This situation demonstrates that the BRICS countries are not in a good position to ensure a clean energy transition. The energy transition data used in the study is a comprehensive indicator that considers various aspects of energy use, such as energy distribution, sustainability, efficiency, and losses in energy distribution. As BRICS countries have a high fossil fuel-dependent energy use, although there is a steady increase in ETI, nevertheless, it is not enough. Hence, slowly increasing ETI becomes inefficient in declining CO_2 emissions in BRICS countries. In this context, BRICS policymakers should increase the use of clean energy in total energy to ensure a reduction in CO_2 emissions. In addition, policymakers should adopt an energy policy that increase the efficiency of current clean energy source use and reduce their cost in generation and distribution to the last users. In this way, the effect of ETI on CO_2 emissions can be turned into a decreasing one.

In the bivariate case, GDP has a reducing effect only in India. In the multivariate case, this result is reversed. This reveals that there is a changing effect of GDP in case of interaction with other factors (e.g. EPS and ETI). The results imply that GDP growth is a polluting factor for BRICS countries. They have been continuing their industrialization process. Therefore, such developing economies require high consumption of natural resources. The need for necessary natural resources, raw materials, and fossil fuels for economic expansion causes a rise in CO_2 emissions. Specifically, economic expansion in the BRICS countries increases environmental pollution through the scale effect. To prevent this, the BRICS countries should develop green strategies to ensure economic growth and revise their current models of economic growth by considering environmental concerns.

EPS can play a significant role in curbing CO_2 emissions. In this study, it is defined that EPS has an increasing effect on CO_2 emissions in multivariate cases. Under the stringent environmental conditions, countries are expected to curb CO_2 emissions. Sarkodie[79] finds that EPS without institutional structures and economic efficiency can have environmentally damaging effects. Also, Kartal et al.[71] conclude that EPS has a varying effect on CO_2 emissions across various levels (quantiles). Compatible with these studies, this research defines that BRICS countries are not pursuing a successful strategy in implementing EPS. According to the OECD,[80] the BRICS countries do not have an efficient carbon tax strategy. Furthermore, the EPS values of Brazil (0.89), Russia (1.17), and South Africa (0.92) are quite low compared to European countries. At COP26, China and India declared that they prefer to gradually reduce coal-fired electricity production rather than phase it out completely.[81] Furthermore, at COP28, China and India did not ratify a commitment to triple their share of renewable energy by 2030.[82] These recent developments imply that the environmental policies of the BRICS countries are not as strict as they should be because they are not willing to give up carbon-intensive coal, which is the most carbon-intensive energy source, and EPS does more harm than good because the environmental policies do not stimulate to encourage eco-friendly decisions by considering environmental concerns. To solve this problem, BRICS countries should use environmental policies effectively, strengthen their institutional structures to reduce CO_2 emissions, and accelerate coal phase-out as compatible with the expected behavior from them.

Future research

Despite analyzing the effects of key determinants (e.g. EPS, ETI, and GDP) on CO_2 emissions, this study has certain research limitations. Due to the structure of the WLMC, the study focuses on three explanatory variables and neglects the ecological effects of energy and environmental technology development indicators. Therefore, future studies can analyze the effect of energy-related R&D investments and environmental patents on CO_2 emissions as well as apply various approaches, such as incremental analysis. In this way, studies can discuss the optimal type of renewable energy for low-carbon development by evaluating the effect of R&D investments on CO_2 emissions.

The second limitation of the study is that it only focuses on the BRICS countries. Although Russia, India, and China are among the countries with the highest CO_2 emitting countries in the world, some big countries, such as the United States, Japan, and Indonesia, also cause severe environmental damage. Therefore, future studies can analyze the top 10 CO_2-emitting countries through using the WLMC approach.

The third limitation of the study relates to the period. Since the ETI and EPS data are available until 2020, the study period ends in 2020/Q4. Future studies could analyze the nexus between the variables for a longer period with updated data.

The last limitation of the study is that the study does not consider subtypes of EPS. Accordingly, future research can consider subtypes of EPS in ensuring low low-carbon environment.

Availability of data and materials

Data will be made available on request.

Consent for publication

The authors are willing to permit the Journal to publish the article.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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