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Article

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Economic Policy Uncertainty, Energy Consumption, Trade Openness and CO_2 emissions: evidence from BRICS Countries

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ABSTRACT

This paper investigated the impact of economic policy uncertainty, energy consumption, and trade openness on CO_2 emissions in the BRICS countries (Brazil, Russia, India, China, and South Africa) from 1991 to 2023. According to the Panel Pooled Mean Group-Autoregressive Distributed Lag Model (PMG-ARDL), economic policy uncertainty has a significant and negative impact on carbon emissions in the long run, while it has an insignificant effect in the short run. Additionally, primary energy consumption has a significant and positive impact on carbon emissions in the short and long run. Economic growth and trade openness have a positive and significant impact on carbon emissions in the long run. The panel causality test by Dumitrescu and Hurlin (2012) indicated a bidirectional relationship between CO_2 and energy consumption, trade openness, and CO_2, but a unidirectional causality from CO_2 to economic policy uncertainty and economic growth. The study proposes making critical changes in energy policies while accounting for economic policy uncertainty; examining the various types of uncertainty and their effects to develop a climate policy based on evidence and facts and focusing on the discovery of alternative sources of clean energy.

Keywords: Economic Policy Uncertainty, Primary Energy Consumption, Brazil, Russia, India, China, and South Africa, Panel Pooled Mean Group-Autoregressive Distributed Lag Model
JEL Classifications: O24, Q4, Q5

1. INTRODUCTION

In 2021, global carbon dioxide emissions rose significantly, reaching a record level of 36.3 billion tons, up 6% from the previous year. This increase is mainly due to the rapid economic recovery from the COVID-19 pandemic, which relied heavily on coal as an energy source (Caglar, 2020). Carbon dioxide emissions from fossil fuel combustion are the primary cause of climate change, as their concentration in the atmosphere has reached the highest level in human history. This trend continues to rise, with carbon dioxide emissions increasing by 1.7% in 2018 and 1.1% in 2023 (IEA, 2023). Despite growing environmental concerns, countries continue to rely heavily on fossil energy sources, exacerbating the problem of environmental degradation (Murshed et al., 2021). Many countries in the world face major challenges in reducing carbon emissions, especially in light of rapid economic growth, increased energy consumption, and increased trade openness. Economic policies and energy consumption play an important role in determining carbon emissions. However, there is significant uncertainty about how these factors will impact carbon emissions. Thus, we are examining the impact of uncertainty in economic policies, energy consumption, and trade openness on carbon emissions and environmental degradation.

The phenomenon of these emissions grows especially important in resource-rich nations that also face high levels of geopolitical risk and economic uncertainty. The five BRICS nations are among the top ten economies that emit the most carbon dioxide in this group of countries (Adams et al., 2020). The huge increase in emissions in the BRICS economies is due to high economic growth, accompanied by increased consumption of the most polluting fossil energy (Danish and Khan, 2019). It contributes more than 23% of the global GDP (Ali et al., 2022). These countries consume about one-third of the world's total energy consumption in 2019, with a projected increase to 40% by 2040 (Zeng and Yue, 2022). The BRICS countries rank among the world's biggest carbon emitters. In 2018, the group accounted for about 42% of global CO_2 emissions (Balsalobre-Lorente et al., 2019; Nathaniel et al., 2021; Zeng and Yue, 2022). Given their high population, an increase in energy consumption is inevitable (Caglar et al., 2022; Saribayevich et al., 2024). While carbon emissions in developed economies decreased from 40% to 25% between 1990 and 2018, they increased in BRICS countries from 27% to 42% during the same period due to their reliance on fossil fuels. The BRICS economies have implemented several kinds of environmental laws and policies, including feed-in tariffs, carbon taxes, and emission reduction initiatives to reduce consumption of energy and combat carbon emissions. Despite setting numerous political goals to achieve carbon neutrality, the desired decrease in energy consumption did not materialize (Durani et al., 2023).

International trade is an important part of global economies and has a profound impact on emissions. Trade openness contributes to an increase in carbon emissions from energy consumption (Shahzad et al., 2017; Cetin et al., 2018; Usman et al., 2022). Trade openness is one of the reasons for carbon emissions in the BRICS countries; the share of the BRICS group in global trade increased significantly from 3.6%, 15%, 16.5%, and 18.1% to 20.9% in 1990, 2010, 2015, 2018, and 2022, respectively (Caglar et al., 2022; World Bank database).

Economic policy uncertainty is a measure of the overall health of a country's macroeconomic institutions. This is because it captures the uncertainty associated with monetary, fiscal, trade, and other macroeconomic policies (Syed and Bouri, 2022). Numerous studies have indicated that uncertainty in economic policies is likely to have a fundamental impact on economic activity, for example, the Arab Spring revolutions, the COVID-19 pandemic, the Russian-Ukrainian war, etc. (Adams et al., 2020; Wen et al., 2022; Selmey and Elamer, 2023). Economic policy uncertainty has increased at an unprecedented rate in the 21st century, with negative impacts on the economy and the environment (Durani et al., 2023). Considering its significant effects on the environment, researchers have observed that EPU is one major determinant of emissions. Therefore, EPU may have a variety of impacts on CO_2 emissions.

Recently, many studies indicated that there are two channels linking uncertainty in economic policies to CO_2 emissions (Wang et al., 2020; Anser et al., 2021; Durani et al., 2023): (1) consumption effect; (2) investment effect. According to the consumption effect, economic policy uncertainty reduces the use of energy- and pollution-intensive goods. As a result, there will be a reduction in CO_2 emissions and environmental degradation. On the other hand, investment impact shows that uncertainty in economic policies hinders investment in renewable energy and R&D, which ultimately leads to CO_2 emissions. Consequently, EPU can increase or decrease CO_2 emissions. Notably, EPU's impact on CO_2 emissions may vary in the short and long run. The fact that CO_2 emissions may respond more quickly to a reduction in investment and output than to changes in technology, inventions, or consumption of renewable energy sources suggests that the link between the short and long runs is not homogenous (Syed and Bouri, 2022). The contradictory findings of previous literature call for further investigation into the impact of economic policy uncertainty on environmental degradation (Syed and Bouri, 2022; Selmey and Elamer, 2023).

This study investigated the impact of economic policy uncertainty, energy consumption, and trade openness on CO_2 emissions in the BRICS countries (Brazil, Russia, India, China, and South Africa) from 1991 to 2023. The empirical results of the study indicate that economic policy uncertainty negatively affects carbon emissions in the BRICS group of countries. The study also reveals that primary energy consumption and trade openness have a positive impact on carbon emissions in these countries. This study also presents proposals to shed more light on environmental regulations in the BRICS group of countries. Given the increasing economic growth, increasing energy demand, rising population, and increasing oil prices, environmental degradation and energy security will represent major challenges for the BRICS countries in the coming years. The practical solution to these problems is to increase consumption and production of green energy, considering the effects of economic policy uncertainty.

This study contributes to the current literature in several ways. First, this study closes a gap by precisely assessing the efficacy of different policy initiatives by examining key factors such as economic policy uncertainty, energy consumption, trade openness, and carbon emissions from 1991 to 2023. We used the cross-sectional dependence (CSD) method, FMOLS, and the Panel Pooled Mean Group-Autoregressive Distributed Lag Model (PMG-ARDL) to get estimates for the study variables in both the short and long term. However, little past research has utilized these methodologies, especially in examining the long-term relationship between these factors in the context of BRICS countries. Third, economists and environmentalists could utilize this study to model the economic determinants of carbon emissions. Policymakers from the BRICS countries can utilize this paper to develop policies relating to carbon neutrality.

We organize the subsequent sections of this paper as follows: The "Review of Literature and Hypothesis Development" section provides an overview of previous research and literature. The "Methodology and Data" section explains the methodology and data used in the study. The section titled "Empirical Findings and Discussions" covers the study's results and provides a detailed analysis and interpretation of them. Finally, the "Conclusion" section is the last part of the study that sums it up.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

This section highlights the literature examining the relationship between economic policy uncertainty, energy consumption, trade openness, and CO_2 emissions.

2.1. Economic Policy Uncertainty and CO_2 Emissions

Economic policy uncertainty (EPU) refers to the negative economic effects of monetary, fiscal, and regulatory policy uncertainty (Pirgaip and Dinçergök, 2020). The economic policy uncertainty index presented by Baker et al. (2016) has received considerable interest from researchers. Recent empirical studies have demonstrated that economic policy uncertainty (EPU) exerts detrimental effects on the economy at both the micro level, encompassing firm investment, and the macro level, encompassing economic growth. During periods of heightened economic policy uncertainty, investment, output, and employment tend to decline, along with research and development (R&D) expenditures and innovation activities (Ahmed et al., 2020; Amarasekara et al., 2022). Another way to look at it is that policy uncertainty is a harbinger of a potential economic downturn because businesses reduce or postpone their consumption and investment when uncertainty increases (Mushtaq et al., 2024). The influence of uncertainty in economic policies on pollution can be observed through its impact on economic growth. EPU discourages firm hiring and investment, which is harmful to economic growth (Liu and Zhang, 2022).

The pursuit of sustainable development goals, whether economic, social, or environmental, has placed examining uncertainty in economic policies at the forefront of major priorities for researchers and policymakers in recent years (Baker et al., 2016). Economic policy uncertainty is an important and effective indicator of ecological deterioration (Adams et al., 2020). Many studies have examined the relationship between economic policy uncertainty (EPU), carbon dioxide (CO_2) emissions, and environmental degradation. Previous research on this topic has yielded uncertain or inconclusive results. Studies indicated a positive or negative relationship, while other research indicated that there was no clear relationship.

Several research investigations have examined the association between economic policy uncertainty (EPU) and carbon dioxide (CO_2) emissions. One of these is by Jiang et al. (2019), who used Granger causality to show that there is a one-way link between EPU and carbon dioxide emissions in the transportation, electricity, and manufacturing sectors.

In the United Kingdom, Adedoyin and Zakari (2020) used autoregressive lagged lags (ARDL) methodology over the period 1985-2017. The study suggests that economic policy uncertainty reduces carbon dioxide emissions in the short term but increases them in the long term. In addition, Pirgaip and Dinçergök (2020) investigated the causal relationship between economic policy uncertainty, energy consumption, and CO_2 emissions in G7 countries. The results indicated that economic policy uncertainty affects carbon dioxide emissions in a few G7 countries (America, Canada, and Germany). Syed and Bouri (2022) indicated that uncertainty in economic policies increases CO_2 emissions in the short term, indicating that high uncertainty in economic policies is responsible for environmental degradation in the short term. In the long run, there is a negative relationship, as uncertainty reduces carbon emissions and thus improves environmental quality. Liu et al. (2020) collected data from a total of fifty-two energy companies based in China. The study highlights that 16 renewable energy companies examined the impact of EPU on the investment performance of different types of organizations. Their research suggests that increased economic policy uncertainty (EPU) negatively affects the investment choices made by companies in the coal and petroleum industries. Conversely, the rise in EPU has stimulated investment in the solar energy sector, geothermal generation, and other sectors related to renewable energy. Anser et al. (2021) point out that economic policy uncertainty negatively affects CO_2 emissions in the short run, but in the long run, economic policy uncertainty has a positive impact on CO_2 emissions. Selmey and Elamer (2023) indicated that the short- and long-term relationship between economic policy uncertainty and carbon emissions in Egypt is positive, demonstrating that economic policy uncertainty does not encourage investment in R&D, innovations, and renewable energy, which raises CO_2 emissions.

According to the available literature, we propose that there is an association between Economic Policy Uncertainty (EPU) and carbon dioxide (CO_2) emissions. The nature of this relationship can vary, either being positive or negative, contingent upon the magnitude of Economic Policy Uncertainty (EPU) and its influence on energy usage, consumption of products that contribute to pollution, investment in research and development (R&D) as well as innovation, and the utilization of renewable energy sources. More precisely, we anticipate that elevated levels of Economic Policy Uncertainty (EPU) will result in a rise in carbon dioxide (CO_2) emissions in the short term. However, in the long term, the association between EPU and CO_2 emissions may become inverse. Therefore, we propose the following hypothesis:

H1: There is an association between economic policy uncertainty and CO_2 emissions.

2.2. Energy Consumption and CO_2 Emissions

Understanding the relationship between energy consumption, economic growth, and carbon emissions is crucial to addressing climate change challenges and achieving the Sustainable Development Goals. Recently, many empirical studies have focused on examining the close relationship between energy consumption, economic growth, and carbon dioxide emissions. For example, Shafiei and Ruhul (2014) analyzed the factors that influence CO_2 emissions for OECD nations using the STIRPAT methodology during the period 1980-2011. The empirical findings show that non-renewable energy use increases carbon dioxide emissions, while renewable energy consumption decreases them. Also, Chen et al. (2016) used a panel cointegration and vector error-correction method to examine the connections between economic activity, energy usage, and environmental factors across 188 nations from 1993 to 2010. The empirical findings demonstrated the presence of long-term relationships among economic growth, energy consumption, and carbon dioxide emissions across all countries. Also, the relationship between energy consumption and carbon dioxide emissions is unidirectional, meaning that changes in energy consumption directly affect carbon dioxide emissions across all economies. Similarly, Wang et al. (2016) investigated the cointegration and causality relationships among economic growth, energy consumption, and CO_2 emissions in the Chinese economy from 1990 to 2012. The cointegration tests indicate that there is a long-term cointegrating link between the variables. The study found a bi-directional causal relationship between economic growth and energy consumption, as well as a unidirectional causal relationship between energy consumption and CO_2 emissions.

Wang and Fang (2018) examined the linkage between economic growth, energy consumption, and CO_2 emissions in 170 economies from 1980 to 2011. The findings concluded that in all the countries, the results of panel cointegration tests indicated that there was a cointegration relationship between the variables and that, over time, there was a significant positive link. Granger causality links between the variables varied among the income-based subpanels, according to the findings of a Granger causality test. Adebayo and Akinsola (2021) Their study aimed to address the following question: Is there an association between GDP growth, consumption of energy, and carbon dioxide emissions in Thailand from 1971 to 2018? The findings showed that (1) changes in Thailand's economic growth were responsible for changes in CO_2 emissions. (b) There exists a positive association between energy consumption and CO_2 emissions in both the short and long term. (c) There is a bidirectional cause-and-effect link between the emission of carbon dioxide (CO_2) and the consumption of energy. Musah et al. (2022) used the CS-ARDL and CCEMG estimators to find the connection between North Africa's energy use and carbon dioxide emissions from 1990 to 2018. The outcomes revealed that the region's environmental quality deteriorated because of increased energy consumption, which had negative effects on CO_2 emissions.

Raihan (2023) used the autoregressive distributed distribution (ARDL) and vector error correction model (VECM) methods to look at the connection between Vietnam's economic growth, energy use, and CO_2 emissions from 1984 to 2020. Empirical results indicated that economic growth and energy consumption lead to environmental degradation through increased CO_2 emissions in the long and short term. Using the distributed autoregressive approach and the Granger causality test, Khan and Khan (2024) analyzed the relationship between carbon emissions resulting from energy consumption and economic development in the Kingdom of Saudi Arabia from 1985 to 2021. The study concluded that there is a positive relationship between energy consumption and carbon emissions. The Granger causality test revealed a unidirectional causality between energy use and carbon dioxide emissions. Finally, Pradhan et al. (2024) explored the link between economic growth, energy consumption, and carbon dioxide emissions by comparing the emerging nations in South Asia with the G-7 countries from 1996 to 2021. To fully understand these complicated relationships, they used a variety of analytical tools, such as panel regression techniques, simultaneous econometric models, and panel autoregressive distributed lag (ARDL) techniques. The results suggested that the use of energy has a significant effect on economic growth in both South Asia and G-7 countries. In addition, the two regions' economic growth positively responds to CO_2 emissions. Moreover, rising GDP per capita in the two regions leads to increased energy consumption. Furthermore, CO_2 emissions have a positive impact on energy use in both categories.

According to previous studies, we hypothesize a relationship between energy consumption and environmental degradation, particularly in terms of increased carbon dioxide emissions. Further research is required to investigate this relationship in greater detail and develop policies that can help improve the efficiency of energy consumption technologies to achieve environmental quality. Thus, we hypothesize the following:

H2: There is a relationship between energy consumption and CO_2 emissions

2.3. Trade Openness and CO_2 Emissions

Numerous pioneering studies have focused on international trade and its impact on economic growth (e.g., Huchet-Bourdon et al., 2018; Raghutla, 2020; Kong et al., 2021; Sunde et al., 2023; Srdelić and Dávila-Fernández, 2024). However, in recent decades, there has been significant interest from researchers and policymakers in examining the impact of trade openness on environmental quality and climate change (e.g., Ertugrul et al., 2016; Jamel and Maktouf, 2017; Dauda et al., 2021; Li and Haneklaus, 2022; Pata et al., 2023; Ghazouani and Maktouf, 2024). Grossman and Kruege's (1991) groundbreaking study, which analyzed the environmental impact of the North American Free Trade Agreement (NAFTA) and examined the relationship between environmental degradation and trade openness, marked a significant advancement in the exploration of this relationship. Consequently, environmental literature began to concentrate on the influence of trade openness on carbon dioxide emissions.

Empirical studies have found conflicting results. Studies have indicated that there is a positive relationship between them, that trade openness is responsible for increasing carbon emissions and environmental degradation (e.g., Shahbaz et al., 2017; Ansari et al., 2020; Li and Haneklaus, 2022; Ashraf et al., 2023; Yahyaoui and Ghandri, 2024), and other studies have indicated that there is a negative relationship, as trade openness can lead to a decrease in carbon emissions (e.g., Zhang et al., 2017; Ghazouani and Maktouf, 2024; Wang et al., 2024).

Chen et al. (2021) examined the relationship between trade openness and CO_2 emissions for the Belt and Road countries over the period from 2001 to 2019. The empirical findings suggest that an increase in trade openness has a significant and positive effect on CO_2 emissions. Also, Dou et al. (2021) assessed the influence of trade openness on CO_2 emissions by examining the China-Japan-ROK Free Trade Agreement from 1970 to 2019. The empirical results revealed that (a) trade openness has positive effects on the greenhouse effect, and adopting the agreement can mitigate the trade openness-induced increase in carbon emissions. (b) Imports lead to higher carbon emissions, whereas exports result in a significant decrease in carbon emissions within a country. (c) Increasing trade openness has a direct impact on carbon emissions, as well as indirect effects via the scale effect, technical effect, and structure effect. Using the ARDL-bound test model, Usman et al. (2022) investigated the role of trade openness in increasing carbon emissions in Pakistan's economy. The empirical findings revealed that Pakistan's trade openness caused the degradation of environmental quality during the study period.

On the other hand, numerous studies suggest a negative linkage between trade openness and carbon emissions, as follows: Amin et al. (2020) explored the association between trade openness and CO_2 emissions. They collected panel data from Asian nations spanning the years 1985-2019. Using panel cointegration and FMOLS techniques. The outcomes showed that trade openness squeezes carbon emissions. Muhammad et al. (2022) employed the Augmented Mean Group (AMG) method and the Westerlund panel cointegration approach to assess the relationship between trade openness and CO_2 emissions in OECD countries. The findings revealed that trade openness has a negative influence on CO_2 emissions in OECD countries. Pata et al. (2023) studied the effect of trade openness on CO_2 emissions for the Association of Southeast Asian Nations (ASEAN). They conducted their study using the panel ARDL estimation and the Dumitrescu-Hurlin panel causality analysis, covering the period from 1995 to 2018. The results found that increased trade openness leads to a decrease in environmental damage.

The impact of trade openness is contingent upon the environmental policies implemented in each country. In developing countries, there are weak environmental rules and low energy prices to support the competition of their products in international markets, and thus low energy use efficiency negatively affects environmental quality (Wan et al., 2015). Free trade may lead to the importation of polluting goods into poor countries with low environmental standards, i.e., so-called pollution haven countries. Free trade and the movement of production factors may shift polluting industries toward pollution-haven countries with weak environmental regulations (Al-Mulali et al., 2015). On the other hand, proponents of the international trade theory explain the positive effect of trade openness on environmental quality by arguing that it promotes competition between nations, encourages the efficient use of scarce resources, and facilitates the transfer of cleaner technologies, which contributes to combating environmental pollution (Wan et al., 2015; Amin et al., 2020). Finally, based on existing empirical evidence, it is likely that trade openness influences environmental deterioration. However, the findings about the relationship between trade openness and the environment are inconclusive and provoke conflict. The characteristics of a country, methodologies, and other factors significantly influence the impact of trade openness on the environment. Furthermore, there is currently a dearth of empirical evidence regarding the varying effects of trade on environmental quality. Hence, the study hypothesis is:

H3: There is a linkage between trade openness and CO_2 emissions.

3. DATA AND METHODOLOGY

3.1. Data

The study is based on annual data for the five BRICS countries (Brazil, India, China, and South Africa) during the period 1991-2023. We chose this period based on the availability of data. Table 1 provides a description of the data sources. The data sources represent uncertainty in economic policy (expressed by the World Uncertainty Index), which represents uncertainty in economic policy and the political aspects of each country in the study (www.World Uncertainty Index.com). CO_2 emissions (measured in millions of tons of carbon dioxide) and primary energy consumption are sourced from the World Energy Statistical Review. GDP per capita in US dollars and trade openness expressed as the ratio of trade volume of exports and imports to GDP are sourced from the World Bank's World Development Indicators (WDI).

3.2. Model Specification

This study aims to look at how economic policy uncertainty (EPU), primary energy consumption (ENC), the size of the economy (GDP), and trade openness (OPT) affect CO_2 emissions in BRICS countries (Brazil, Russia, India, China, and South Africa). And then, we use heterogeneous causality testing to determine short-run causality between these variables. Generally, we formulated the model using the following panel data equation:

$$CO2_{it} = \beta_0 + \beta_1\, EPU_{it} + \beta_2\, ENC_{it} + \beta_3\, GDP_{it} + \beta_4\, OPT_{it} + \varepsilon_{it} \quad (1)$$

When we algorithmize equation (1), we obtain the following form:

$$LCO2_{it} = \beta_0 + \beta_1\, LEPU_{it} + \beta_2\, LENC_{it} + \beta_3\, LGDP_{it} + \beta_4\, LOPT_{it} + \varepsilon_{it} \quad (2)$$

The symbols i (i = 1,….,N) and t (t = 1,…….,T) stand for countries and periods, respectively. The symbol L indicates the natural logarithm. We used logarithms to avoid problems related to the distributional properties of the data series (Selmey and Elamer, 2023). β_1‘β_2‘β_3‘β_4 represent the independent variables' parameters that must be estimated. These parameters represent the elasticities of the coefficients of policy uncertainty (*EPU*), primary energy consumption (*ENC*), economic size (*GDP*), and trade openness (*OPT*), respectively. ε_{it} represents the error term, which β_0 represents the fixed intercept (the fixed effect of the countries involved). We assume that EPU increases environmental degradation if ($\beta_1 > 0$) and otherwise when ($\beta_1 < 0$). We assume that ENC increases environmental degradation if ($\beta_2 > 0$) and otherwise when ($\beta_1 < 0$). We assume that GDP increases environmental degradation if ($\beta_2 > 0$) and otherwise when ($\beta_1 < 0$) and assume that OPT increases environmental degradation if ($\beta_2 > 0$) and otherwise when ($\beta_1 < 0$).

The study employed the Pooled Mean Groups-Autoregressive Distributed Lag (PMG-ARDL) methodology, which is characterized

Table 1: Description of data and sources

Indicator	Abbreviation	Measurement	Source
CO_2 emissions	CO_2	Million tonnes of carbon dioxide	Statistical Review of World Energy
Economic policy uncertainty	EPU	World Uncertainty Index (WUI)	http://www.policyuncertainty.com
Energy consumption	ENC	Exajoules	Statistical Review of World Energy
GDP per capita	GDP	GDP per capita (current US$)	WDI
Trade openness	OPT	Trade (% of GDP)	WDI

Source: The authors. EPU: Economic policy uncertainty, ENC: Energy consumption, OPT: Trade openness by its ability to explain short- and long-term effects. To apply this methodology, the following steps were followed:

3.2.1. Cross-sectional dependence tests

A cross-sectional dependence test for panel data is one of the most important diagnostics that a researcher should perform before conducting panel data analysis and estimating the model. In other words, in order to obtain more accurate long-run parameter estimates, the researcher must first test cross-sectional dependence between countries and examine the stationarity properties of the series (Tugcu, 2018). Therefore, estimating cross-sectional dependence between countries becomes one of the most crucial diagnostic tests, as observations no longer stand alone but now significantly influence and depend on each other. More importantly, it helps us apply more appropriate unit root tests and cointegration tests, as previously mentioned. The current study employs three cross-sectional dependence tests: the Breusch and Pagan (1980) LM, the Pesaran (2004) scaled LM, and the Pesaran (2004) CD. We can calculate the test statistics for these tests, represented by LM, CD_{LM} and CD, respectively, using the following formula (Sarafidis et al., 2009).

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \tag{3}$$

$$CD_{LM2} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T\hat{\rho}_{ij}^{2}-1\right) \tag{4}$$

$$CD = \sqrt{\frac{2T}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \tag{5}$$

The symbol ($\hat{\rho}_{ij}$) represents the correlation coefficients derived from the model's residuals. The residuals become cross-sectionally dependent if we reject the null hypothesis.

3.2.2. Panel unit root tests

This study utilized the augmented unit root test (CADF) and the CIPS test because they could potentially rely on the cross-section, as demonstrated by the cross-sectional dependent tests previously mentioned. There were two types of unit root tests used for the panel data, as suggested by Pesaran et al. (2008). The first was the cross-sectional C.I.P.S. test for Im, K.S., Pesaran, M.H., and Shin, Y. The second test was the cross-sectionally augmented Dickey-Fuller C.A.D.F. test. The second generation of unit root tests, or C.A.D.F. (Westerlund et al., 2016; Azam et al., 2021), shows that all variables are stationary and that there is cross-sectional dependence between countries most of the time. Given the stationary null hypothesis, we can present the C.A.D.F. test statistic as follows (Alataş, 2022):

$$\begin{aligned}\Delta y_{it} &= \omega_0 + \omega_1 y_{i,t-1} + \omega_2 \bar{y}_{t-1} \\ &+ \sum_{j-1}^{m}\beta_{1ij}\Delta\bar{y}_{i,t-j} + \sum_{k=0}^{n}\beta_{2ij}\Delta y_{t-j} + \mu_{it}\end{aligned} \tag{6}$$

Pesaran (2007) demonstrated that the C.A.D.F. unit root test for panel data yields robust and satisfactory results, even for relatively small values of both the segment N and the time T. If a series is non-stationary at the level, estimating it using the panel data least squares method will produce spurious findings (Alataş, 2022). The C.I.P.S. statistic is obtained by evaluating the given equation after obtaining the C.A.D.F. statistic for each cross-section (Azam et al., 2021).

$$CIPS = N^{-1}\sum_{i=1}^{N}CADF_i \tag{7}$$

3.2.3. Cointegration test

We use the panel bootstrap cointegration test to analyze the potential long-term cointegration relationship between non-stationary series. According to Westerlund and Edgerton's (2007) test, the null hypothesis for this test demonstrates that cointegration exists in panel data. "Their null hypothesis asserts the absence of cointegration." The Lagrange multiplier, which was created by McKoskey and Kao in 1998 and is the basis of this test, gives good results for small samples and lets cross-sectional dependence between cross-sectional units be shown (Alataş, 2022).

3.2.4. PMG-ARDL methodology

Dumitrescu and Hurlin (2012) developed the Pooled Mean Groups-Autoregressive Distributed Lag methodology, which this study uses to estimate the short-run and long-run dynamic relationships of a series of variables. Several advantages distinguish this model from other co-integration techniques, such as its ability to integrate the series at the level I (0), the first difference, I (1), or both, while avoiding integration at the second difference, I (2). Therefore, with this availability, we can apply the ARDL methodology to estimate both short- and long-term effects, considering a sufficient number of lags. (ii) This methodology is suitable for small-sized samples and provides robust cointegration results for small-sized samples (Azam et al., 2021). Dumitrescu and Hurlin (2012) highlight the last and most significant benefit of this technique, which is its application within the Panel A.R.D.L. methodology. The formula for this model is (p, q), where p represents the lag of the dependent variable and q represents the lag of the explanatory variables. This model can be formulated as follows:

$$\begin{aligned}LCO2_{it} &= \& a_0 + \varphi_i\sum_{j=1}^{p}\Delta LCO2_{it-j} + \theta_i\sum_{j=1}^{q}\Delta LEPU_{it-j} \\ &+\omega_i\sum_{j=1}^{q}\Delta LENC_{it-j} + \beta_i\sum_{j=1}^{q}\Delta LGDP_{it-j} + \delta_i\sum_{j=1}^{q}\Delta LOPT_{it-j} \\ &+\pi_i + \lambda_1 LCO2_{it-1} + \lambda_2 LEPU_{it-1} + \lambda_3 LENC_{it-1} \\ &+\lambda_4 LGDP_{it-1} + \lambda_5 OPT_{it-1} + \varepsilon_{it}\end{aligned} \tag{8}$$

Where, $LCO2_{it}$ represents the dependent variable for cross-section (i) and time (t). Δ denotes the difference. ϕ, θ, ω, β, δ refers to the short-run coefficients. λ_1, λ_2, λ_3, λ_4, λ_5 refers to the long-run coefficients. p, q, q, q, q represents the maximum number of lags. ε_{it} denotes the error term. Hence, The Panel's Pooled Mean Group-Autoregressive distributed lag model (PMG-ARDL) is used in this study and is described as follows (Adams et al., 2020):

$$\Delta Ly_{it} = \varnothing_i ECT_{it} + \sum_{j=0}^{q-1} \Delta Lx_{it-j} \beta_{ij} + \sum_{j=1}^{p-1} \psi_{ij} \Delta Lx_{it-j} + \varepsilon_{it} \quad (9)$$

$$ECT_{it} = y_{it-1} - X_{it}\theta \quad (10)$$

In equations (9) and (10), the variable y represents the dependent variable, which is CO_2. The vector X represents the set of explanatory variables, namely EPU, ENC, GDP, and OPT. All these variables have the same lag q, which varies across different nations (i) at different times (t). Δ represents the difference operator, and θ is the coefficient of the long run, which produces estimates of ψ and β at convergence.

4. EMPIRICAL RESULTS AND DISCUSSION

This section presents the initial statistical tests and the main empirical results. The researcher first tests cross-country dependence between countries. The results shown in Table 2 rejected the null hypothesis, indicating independence between countries for all variables. The results show that there is cross-sectional dependence between countries. This is because the Pesaran scaled LM and Pesaran CD tests were significant at a 1% significance level, and the Breusch-Pagan LM test statistic was significant at a 5% significance level. This indicates that one member of the BRICS group's shock significantly affects the other members. This result, from the perspective of the aforementioned methodology, also assists in identifying and applying more suitable unit root and cointegration tests for the model (Alataş, 2022).

To determine the stationary of all variables in the estimated model, the next step involves unit root tests that allow for cross-sectional dependence. To achieve this, we apply the panel data unit root tests (C.I.P.S. and C.A.D.F.) by Pesaran et al. (2008).

Tables 3 and 4 display the results of the C.I.P.S. and C.A.D.F. tests. They show that all the variables used in the model (LCO_2, LEPU, LENC, LGDP, and LOPT) are stationary at the first difference. At 1% and 5% significance levels, both tests rejected the null hypothesis of a unit root for all variables. This suggests that all variables' time series integrate in the same order (first difference).

In the next step, to analyze the potential long-run cointegration relationship between the time series of variables, we employ the panel bootstrap cointegration test. According to Westerlund and Edgerton (2007), the null hypothesis of this test indicates that there is no cointegration, as this test is based on the Lagrange multiplier of McKoskey and Kao (1998).

According to the results in Table 5, the ADF test statistic for cointegration is −3.393782 and the (P = 0.0003), which is significant at the 1% significance level. Thus, we reject the null hypothesis of no cointegration and conclude that there is cointegration between the variables in the long run.

The results of (a) cross-sectional dependence, (b) stationarity tests, and (c) cointegration tests showed that there is cross-sectional dependence and stationery of the variables, and that they are all stationarity at the first difference. There is also a long-term cointegration relationship between the variables. The next step is to estimate the model parameters in both long and short terms using the PMG-ARDL methodology. We must determine the optimal lags periods for the model using the Akaike Information Criteria (AIC) test before estimating the model using the PMG-ARDL method. The results were as follows:

Table 2: Cross-section dependence test findings

Test	Prob.	Statistic
Breusch-Pagan LM	0.0125**	22.56121
Pesaran scaled LM	0.0050*	2.808773
Pesaran CD	0.0011*	3.273493

*, and ** indicate statistical significance at the 1% and 5% levels, respectively. Source: Prepared by the authors based on EViews 12 outputs

Table 3: C.I.P.S. test findings

Variable	C.I.P.S.	
	Δ (Prob.)	Level (Prob.)
LCO2	0.0441**	0.3827
LEPU	0.0000*	0.1115
LENC	0.0002*	0.4913
LGDP	0.0028*	0.6061
LOPT	0.0014*	0.7369

*, and ** indicate statistical significance at the 1% and 5% levels, respectively. Source: Prepared by the authors based on EViews 12 outputs.

Table 4: C.A.D.F. test findings

Variable	C.I.P.S.	
	Δ (Prob.)	Level (Prob.)
LCO2	0.0376**	0.1485
LEPU	0.0000*	0.1256
LENC	0.0005*	0.3261
LGDP	0.0086*	0.7860
LOPT	0.0030*	0.5289

*, and ** indicate statistical significance at the 1% and 5% levels, respectively. Source: Prepared by the authors based on EViews 12 outputs

Table 5: Kao Cointegration test findings

Augmented Dickey–Fuller (ADF)	Kao Cointegration Test	
	Prob.	t-statistic
	0.0003*	-3.393782

* indicate statistical significance at the 1% level. Source: the authors based on EViews 12 outputs

The results in Table 6 indicate that the optimal lag length using the AIC test is ARDL (4, 1, 1, 1, 1). Therefore, we can carry out the estimation process using the PMG-ARDL model after determining the optimal lag length for the model variables. After the estimation process was completed, the results were as shown in Table 7:

Table 7 makes it clear that economic policy uncertainty has a significant and negative long-term effect on carbon dioxide emissions in the BRICS group, with a significance level of 5%. This is because the empirical results showed that a 1% increase in economic policy uncertainty causes a 0.027% drop in carbon dioxide emissions over the long term. This means that increasing the EPU index improves environmental quality over time. This result is consistent with the results of many other

Table 6: Akaike Information Criteria test findings

Specification	AIC	Model
ARDL (4, 1, 1, 1, 1)	−6.434615*	4
ARDL (3, 1, 1, 1, 1)	−6.405418	3
ARDL (1, 1, 1, 1, 1)	−6.368568	1
ARDL (2, 1, 1, 1, 1)	−6.364786	2

Source: the authors based on EViews 12 outputs

Table 7: Long-run and short-run estimations of parameters results

Dependent variable (LCO_2)	Long - run results		
Independent variables	Coefficient	t-statistics	P-value
LEPU	−0.026823	−2.288457	0.0244**
LENC	1.080245	18.88692	0.0000*
LGDP	0.021231	3.033407	0.0032*
LOPT	0.084826	4.974245	0.0000*
Short - run results			
ECT (−1)	−0.378415	−5.137223	0.0000*
D (CO_2 [−1])	−0.01124	−0.262322	0.7937
D (CO_2 [−2])	0.012648	0.18221	0.8558
LEPU	0.001194	0.075696	0.9398
LENC	0.673808	6.151268	0.0000*
LGDP	0.006989	0.435112	0.6645
LOPT	−0.006415	−0.153195	0.8786

*, and ** indicate statistical significance at the 1% and 5% levels, respectively.
Source: The authors based on EViews 12 outputs

studies (e.g., Jiang et al., 2019; Syed and Bouri, 2022; Liu and Zhang, 2022). This can be explained by the fact that increased uncertainty can lead to a reduction in the consumption of energy-intensive products, which in turn leads to a reduction in carbon dioxide emissions. Furthermore, economic policy uncertainty influences economic activity, causing disruptions in industry and discouraging household consumption. The decrease in household consumption leads to a decrease in carbon dioxide emissions, in addition to reducing energy consumption (Liu and Zhang, 2022). Therefore, a decline in production, consumption, and investment can reduce carbon emissions. These results suggest that economic policy uncertainty can have a negative impact on economic growth by reducing investment and productivity (Wen et al., 2022). Furthermore, it is important to note that the impact of economic policy uncertainty on carbon dioxide emissions may vary depending on several factors, including the type of uncertain economic policy, the country's economic conditions, and the expectations of businesses and consumers (Wang et al., 2021; Iqbal et al., 2023).

Table 6 also shows that the effect of primary energy consumption on carbon dioxide emissions is significant and positive in the long and short terms at a significant level of 1%, which is consistent with economic theory's expectations. An increase in primary energy consumption by 1% leads to an increase in carbon emissions by 1.08% in the long term and by 0.67% in the short term. This result shows that the BRICS countries are heavily dependent on the use of primary energy, which pollutes the environment. As a result, these countries must gradually eliminate dependence on highly polluting traditional energy and choose clean sources such as hydropower, wind energy, solar energy, and others to achieve environmental sustainability. The positive relationship between energy consumption and CO_2 emissions discovered by this study is consistent with several applied studies, including (Acheampong et al., 2019; Khan et al., 2019; Adams et al., 2020; Anser et al., 2021; Islam et al., 2021; Musah et al., 2022; Shabir et al., 2022).

The results of Table 6 showed that there is an insignificant short-term relationship between average per capita GDP and carbon dioxide emissions. However, the relationship was statistically significant and positive in the long term at a significant level of 1%, where a 1% increase in average per capita GDP leads to a 0.02% increase in carbon emissions in the long term. This is in line with economic theory's expectations, as an increase in per capita national income leads to an increase in demand, accelerates the process of manufacturing goods and services, and consequently increases carbon emissions (Shah et al., 2022). This result is consistent with the findings of many studies, including (Adams and Nsiah, 2019; Waqih et al., 2019; Adams et al., 2020; Dauda et al., 2021; Kongkuah et al., 2022; Zafar et al., 2022).

The results in Table 6 also indicated that the short-term effect of trade openness on carbon dioxide emissions in BRICS countries is insignificant. However, at a 1% significance level, it is positive and significant in the long term, where a 1% increase in trade openness in the BRICS countries leads to a 0.085% increase in carbon emissions. This result is consistent with many other studies, such as (Lv and Xu, 2019; Jun et al., 2020; Chhabra et al., 2022; Kongkuah et al., 2022; Shabir et al., 2022). Trade openness plays a vital role in increasing the flow of goods and services and expanding economic output. Trade is a major sector for carbon dioxide emissions from the manufacturing sector. Carbon dioxide emissions are embodied in production processes for export and in final domestic demand for imports. Although countries are shifting their resources to focus on project efficiency and employing many environmentally friendly technologies to balance trade and carbon emissions issues, cleaner and more sustainable production processes remain a key issue for BRICS countries, and international trade and growth are the dominant determinants for CO_2 emissions (Li and Haneklaus, 2022).

The error correction term (ECT) regulates the rate at which adjustment occurs. At the 1% level, the ECM value confirms that the ECT is highly significant and negative. This finding suggests that there is a consistent and stable association between the natural logarithms of EPU, ENC, GDP, OPT, and CO_2 emissions. The ECT value indicates that the rate of adjustment takes approximately 38% of a year to reach long-term equilibrium. In other words, the whole adjustment takes place over a period of approximately 3 years to achieve a level of long-term equilibrium (Selmey and Elamer, 2023). The results showed that a 38% correction occurs in the following year when CO_2 emissions in a given year deviate from the long-term equilibrium level (Brini et al., 2017).

We employ the Dumitrescu and Hurlin (2012) test to examine the causal relationship between the model variables (Zakari et al., 2021). Table 8 demonstrates a unidirectional causal relationship from carbon emissions (CO_2) to economic policy uncertainty (EPU) and the average per capita gross domestic product (GDP). There is also a bidirectional causal relationship between carbon emissions (CO_2), primary energy consumption (ENC), and

Table 8: Dumitrescu and Hurlin (2012) test findings

Causality flow	Null hypothesis	W-Stat	P-value
CO_2→EPU	EPU does not cause CO_2	2.55107	0.7469
	CO_2 does not cause EPU	5.70632	0.0013*
ENC↔CO_2	ENC does not cause CO_2	5.73191	0.0012*
	CO_2 does not cause ENC	8.62058	4.E-09*
CO_2→GDP	GDP does not cause CO_2	3.09229	0.412
	CO_2 does not cause GDP	7.43215	2.E-06*
OPT↔CO_2	OPT does not cause CO_2	8.70627	2.E-09*
	CO_2 does not cause OPT	10.2458	1.E-13*
ENC→EPU	ENC does not cause EPU	6.03887	0.0004*
	EPU does not cause ENC	3.05774	0.4304
ENC→GDP	GDP does not cause ENC	3.3453	0.2924
	ENC does not cause GDP	5.93377	0.0006*
ENC↔OPT	OPT does not cause ENC	6.02817	0.0004*
	ENC does not cause OPT	10.8362	2.E-15*
OPT↔GDP	OPT does not cause GDP	4.67466	0.0229**
	GDP does not cause OPT	11.5478	0.0000*

*, **The rejection of the null hypothesis at significance levels of 1% and 5%, respectively. Source: The authors based on EViews 12 outputs.

Table 9: Panel-FMOLS estimation findings

Variables	Coefficient	t-Statistic	Prob.
LEPU	−0.189376	−1.780256	0.0774**
LENC	1.096505	24.11004	0.0000*
LGDP	−0.199649	−3.582085	0.0005*
LOPT	0.10126	1.773971	0.0785**

*, and ** indicate statistical significance at the 1% and 5% levels, respectively. Source: The authors based on EViews 12 outputs

openness to trade (OPT). Also, there is a unidirectional causality from primary energy consumption (ENC) to economic policy uncertainty (EPU) and GDP per capita. A bidirectional feedback relationship exists between primary energy consumption (ENC) and trade openness (OPT). Finally, we observe a bidirectional feedback relationship between average per capita GDP (GDP) and trade openness (OPT).

In order to verify the quality of the results of the estimated model, we relied on one of the econometric techniques to deal with the problem of heterogeneity in estimation (Pedroni, 2004; Kao et al., 1999). Given the significance of this methodology, we apply the panel-fully modified least squares with weighted estimation (Panel-FMOLS) technique to evaluate the estimated model parameters (Zakari et al., 2021). As shown in Table 9, the estimation results indicate that economic policy uncertainty has a statistically significant and negative impact on carbon emissions in BRICS countries. On the other hand, the results show that primary energy consumption has a statistically significant and positive impact on carbon emissions. This is consistent with the results of the PMG-ARDL estimation method. The estimation results also indicate that per capita GDP and trade openness have a statistically significant impact on carbon emissions in BRICS countries. Finally, the analysis of the quality and robustness of the estimated model above aligns with and validates the results of the PMG-ARDL estimation method.

5. CONCLUSION

The study aimed to investigate the impact of economic policy uncertainty, primary energy consumption, and trade openness on CO_2 emissions in BRICS countries (Brazil, Russia, India, China, and South Africa) during the period 1991-2023 due to the availability of data during that period. The study employed the PMG-ARDL methodology, one of the more modern econometric techniques. The study results found that (1) economic policy uncertainty has a statistically significant and negative impact on long-run carbon emissions. This result is consistent with several studies, (e.g., Jiang et al., 2019; Syed and Bouri, 2022; Liu and Zhang, 2022). Economic policy uncertainty has a positive impact on long-term environmental quality because it causes a decrease in production, consumption, investment, and traditional energy consumption. (2) In the BRICS countries, primary energy consumption has a significant and positive impact on carbon emissions in the short and long term. This result was consistent with many studies, including (e.g., Khan et al., 2019; Sarkodie et al., 2020; Islam et al., 2021; Musah et al., 2022).

The consumption of primary energy has negative effects on the environment's quality in the short and long term. A higher standard of living and the demand for more energy-consuming products with high carbon dioxide emissions correlate with income improvement. Therefore, governments of relevant countries should encourage the use of renewable energy or clean energy sources to reduce CO_2 emissions (Qiao et al., 2019; Sharif et al., 2019). Achieving this will require a high level of investment in research and development to promote the technologies needed to develop and design more efficient energy systems to decouple economic growth from environmental pollution (Adams et al., 2020). Finally, ignoring economic policy uncertainty may lead to unfavorable outcomes for climate and CO_2 emissions policies. Therefore, it can have a negative impact on the long-term decision-making process. For example, overestimating uncertainty hinders the incentive to invest in low-carbon projects, thus increasing risks in the structure of the fossil fuel economy. However, underestimating uncertainty can miss the advantages of early moves, which can lay the foundation for stronger and more sustainable growth (Adams et al., 2020; Workman et al., 2020).

Building on the above, future research interested in policy uncertainty should concentrate on examining the various types of uncertainty, including risk and ambiguity, and appropriately identifying them. More importantly, study their effects to develop a climate policy based on evidence and facts. Finally, this research highlights the intricate interplay between economic factors and carbon dioxide emissions in developing economies like BRICS countries. The study's findings can inform policymakers to design appropriate strategies to reduce carbon emissions and promote sustainable development.

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