The cyclical and asymmetrical impact of green and sustainable technology research (GSTR) on carbon dioxide emissions (CO2) in BRICS economies: Role of renewable energy consumption, foreign direct investment, and exports

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Abstract

Environmental degradation is harming the sustainable development of all societies by reducing the availability of resources for development. And environmental pollution is largely due to the use of fossil fuels, like natural gas, petroleum, coal, heavy oil, bitumen, and oil shales. According to many researchers and environmentalists, clean technologies have been considered an effective method to deal with environmental pollution. Thus, governments and enterprises have invested a significant amount in green research and development expenditures for green and sustainable research to improve clean technologies. However, cyclical fluctuations (increasing in the boom period and declining in the recession) could badly affect the research and development expenditures and green and sustainable research. Moreover, the pro-cyclicality in green and sustainable technology research may have a non-linear effect on environmental sustainability. However, there are no empirical studies on the non-linear link between green and sustainable technology research and environmental sustainability. This paper explored the asymmetrical relationships between green and sustainable technology research and environmental sustainability among the BRICS states, along with foreign direct investment, renewable energy use, and exports as control variables. The data was analyzed by second and third-generation economic techniques such as Slope Heterogeneity and Cross-Section Independence Test, Unit Root Test, structural break unit root test, Panel Cointegration with Structural Breaks cointegration tests, CS-ARDL, AMG, FMOLS, and Dumitrescu-Hurlin Panel Causality test. The results showed that positive shocks to green and sustainable technology research and renewable energy consumption are proper to mitigate carbon dioxide emissions (short- and long-run). Meanwhile, negative shocks to green and sustainable technology research, gross domestic product, foreign direct investment, and exports increase carbon dioxide emissions.

Keywords: Green and sustainable technology, business cycles, CO_2 emissions, renewable energy consumption.

1. INTRODUCTION

Environmental deterioration and global warming have enormously affected the long-term economic development and living conditions of people, especially in emerging economies. As the world faces an increasing number of environmental threats, scholars and policymakers have been seeking ways to find sustainable solutions and switch to sustainable development (United Nations, 2013). Many governments are adopting the ‘green growth model’ to set the course for a green economy. Experts and ecologists believe that sustainable growth mandates competencies that allow for managing complex and abrupt situations. Instead of seeking short-term gains through advancement in brown technologies, technological progress should be focused on developing green technologies (Capassoa, Hansenbcd, Klitkoua, et al., 2019). Some emerging economies, particularly the BRICS (Brazil, Russia, India, China, and South Africa), are making incremental progress towards the green economy model. Global agencies predict that these economies hold the key to the future of sustainable development due to the massive size of their population (41.4 percent of the world) and economic contributions (24.6 percent of global GDP, 2019) (World Bank, 2020). There is no doubt that these states have transformed their economies, created opportunities, and uplifted billions from poverty. Still, it is equally alarming that these countries have become the epicenter of the green-house gases (GHGs), carbon dioxide emissions (CO_2e), and air pollution in the world. The green and sustainable technologies adoption (GST) is considered the most effective way to mitigate climate change's harmful effects and rising global temperatures (Bourgeon & Hovsepian, 2017). In response to global pressures, the BRICS nations have also initiated several green policies, regulations, and funding to encourage the research and development in renewable energy, GST, and energy efficiency. Despite this surging interest, no past study has linked research in green and sustainable technologies (RGST) to CO_2e. If a link exists, do non-linearities in RGST impact the environment quality? Furthermore, what mechanism regulates this relationship? Before seeking an explanation to those questions, it is pertinent to briefly discuss the effect of pollution, RGST, eco-innovation, and economic cycles in BRICS countries for better understanding.

1.1 *The state of environmental pollution: A BRICS perspective*

In 2012 alone, the BRICS states were responsible for nearly 40.6 percent of global GHGs (World Bank, 2020). Khattak, Ahmad, Khan, and Khan (2020) reported that these economies were among the top-seven CO_2-emanating states in 2014, attributing to high industrial production, fossil fuel use, and exports in these economies. According to the World Bank (2017), the BRICS CO_2e (27 percent)

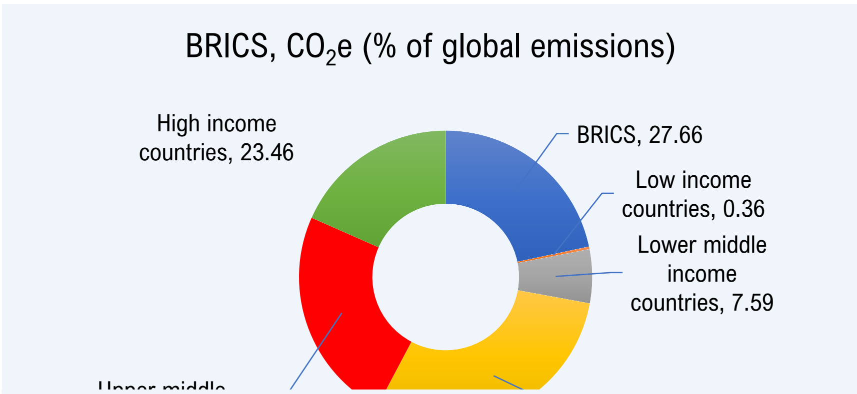

Figure 1. Carbon emissions contribution, BRICS vs. others (% of global emissions).

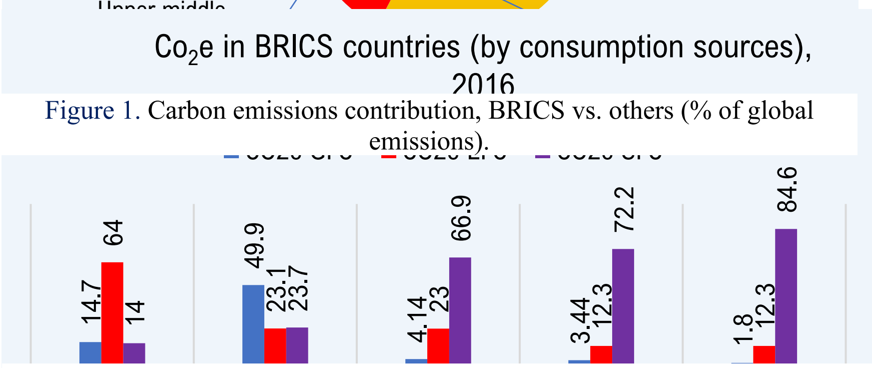

Figure 2. CO_2e by different sources in BRICS (%). Abbreviations: SFC= Solid-fuel consumption; LFC = Liquid-fuel consumption; GFC= Gaseous fuel consumption

was higher than low (0.36 percent), lower-middle (7.59 percent), and higher-income (23.48 percent) economies, even though they were lesser than middle-income (38.09 percent) and upper-middle (30.51 percent) economies (see Figure 1). As most human-caused CO_2e come primarily from the burning of fossil fuels (e.g., hydrocarbon gas liquids, natural gas, petroleum, and coal), it is essential to understand the sources of CO_2e across the BRICS states. As seen in Figure 2, carbon emissions from the consumption of gaseous, liquid, and solid fuels in Russia (49.93 percent), Brazil (63.99 percent), South Africa (84.66 percent) were higher than other member states in 2016, respectively. Solid and liquid fuels appear to be the primary sources of CO_2e in the BRICS economies.

1.2 *An overview of progress in eco-related research and technologies in the BRICS economies*

The BRICS states have been actively engaging and funding technological development and research concerning GSTs, environment preservation, renewables, energy efficiency, alternative fuels, and sustainability (Sharda, 2016). The environmental policies in these countries have focused on two fundamental principles of sustainable development: 1) industry and HEIs are encouraged to buy or embrace existing GST; 2) institutes should invest in GST-related R&D to develop new or improved green technologies. Figure 3 shows that although China was the top CO_2 emitters, it had the highest GST output share (81.05 percent) among BRICS states in 2016. Ahmad, Khan, Rahman, and Khan (2019) supported that China has devoted strenuous efforts to formulate environmental-related policies and strategies to deal with global climate change. According to a recent OECD report (OECD, 2018), China has become the fifth largest country in filing eco-related patent applications from 2010-2014. Chinese eco-patent applications accounted for almost four percent of the world stock, increasing from merely 0.2 percent in the past twenty years. Compared to a minor growth (three-times) in the OECD countries, eco-innovations in China have impressively multiplied sixty times between 1990-2014. In Figure 3, it is evident that, apart from China and Russia, the GST development (GSTD) in India (12.37%), Brazil (2.15%), and South Africa remains unimpressive.

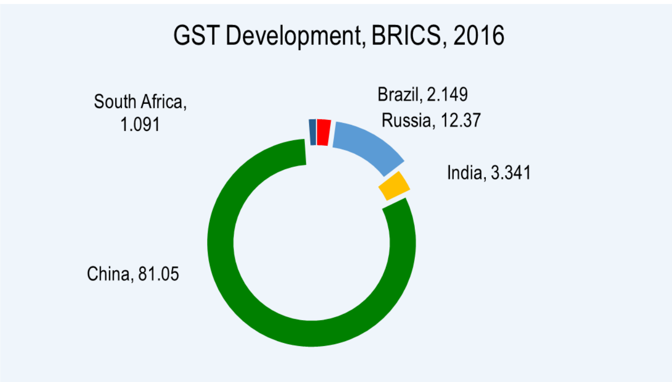

Figure 3. Green and sustainable technology development in BRICS, 2016.

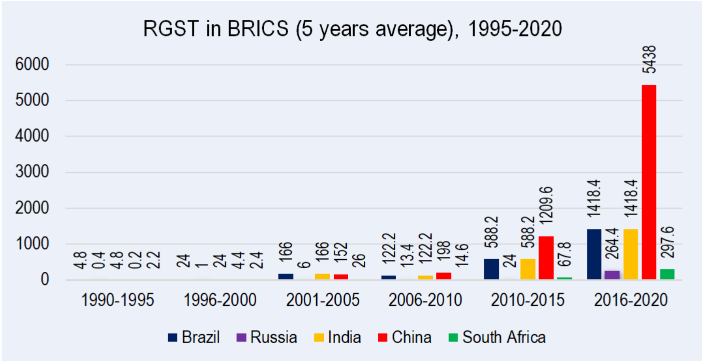

Figure 4. Sector-wise GSTD, BRICS (% of total GST output).

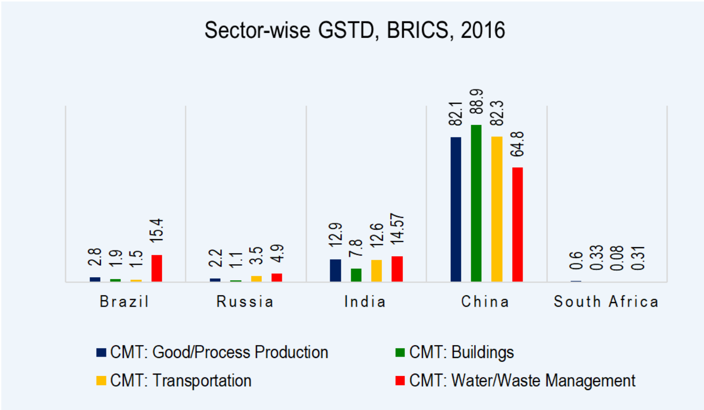

Figure 5. Partnerships in GSTD (by sector), BRICS (% of total GST output), 2016.

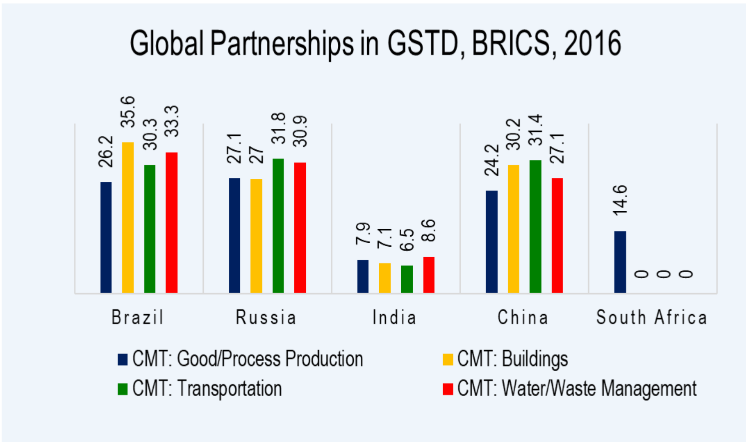

Figure 6. Progress in RGST in BRICS economies from 1990-2020

As seen above, the progress in green and sustainable technologies mainly represented four sectors. Figure 4 demonstrates that China, compared to other BRICS nations, was leading in all sectors, with 82.09, 88.89, 82.28, and 64.82 percent share in production or process of goods, building, transportation, waste management sectors, respectively. India also demonstrated promising prospects at second place in almost all categories, along with Brazil showing an impressive share in the waste-management sector. Additionally, these countries have also initiated partnerships and several initiatives for developing green and sustainable technologies. The establishment of the New Development Bank (NDB) and the

BRICS Forums are prime examples of these international collaborations. All member states have been jointly collaborating within the group and beyond to promote research, infrastructure development, and sustainable development practices across academia, society, and the economy. Figure 5 illustrates the sector-wise global partnerships of BRICS economies in 2016. Except for South Africa, the BRICS economies appear to be making swift progress in forming global GSTD partnerships.

1.3 *Economic cycles and BRICS economies*

A possible explanation for the country-wise differences in RGST and GSTD resides in the distinct characteristics of economic cycles, asymmetries, and non-linearities across different economies. For policymakers and governments, an economic cycle is a crucial tool for analyzing an economy, mainly constituting four economic events, i.e., expansion, peak, contraction, and trough. Conceptually, economic cycles can be defined as the upward and downward fluctuations of the gross domestic product with its natural growth rate over an extended period. Of significance to the present context, the economic cycles of the BRICS states in the past three decades are characterized by periods of expansion, peaks, contractions, and troughs. Prior theory and research strongly assert that investments in eco-related innovation and R&D activities are sensitive to economic cycles because investors and governments tend to invest during economic expansion and boom (rather than recessions and contractions). Assuming that the shifts in RGST are intertwined with the output of eco-related patent applications, innovation, and GSTD, then it is rational to assume that RGST may depend on economic cycles and environmental pollution. Figure 7 illustrates that RGST has been, to a great extent, consistent with economic cycles in BRICS between 2007Q1-2018Q4. Despite that, there is no published theoretical or empirical evidence of this relationship.

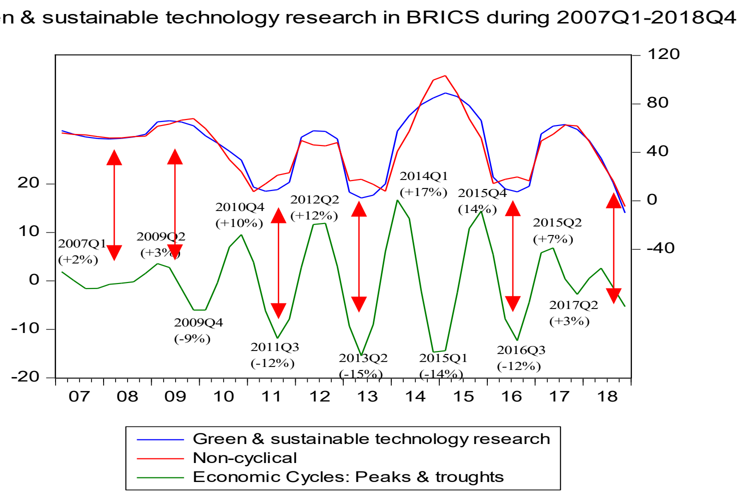

Figure 7: Economic cycles and RGST, BRICS

Note. This figure represents a full sample asymmetric (Christiano-Fitzgerald) frequency filter. Cycle periods include low (4.0) and high (8.0). The stationary assumption is assumed to be I(1) random walk.

Therefore, this study's primary purpose is to offer an initial case for the link between RGST and CO_2e in BRICS states using the latest econometric method. This paper makes several contributions. First, it offers the first conceptual and empirical framework for the nexus between RGST, GDP, exports, renewable energy consumption, FDI, and CO_2e in BRICS nations. Second, the paper combines social and economic factors to offer an alternate explanation for the role of RGST in enhancing environmental pollution. Third, this work extends beyond conventional models by unwrapping the complex dynamics of the cyclicality of RGST and its subsequent environmental impact.

The following sections are categorized as follows. Literature review in section 2 comes first. And section 3 and 4 overview the conceptual framework and methodology, respectively. Section 5 and 6 present interpretations, discussions, and conclusion and policy recommendations.

2. LITERATURE REVIEW

This following unit offers a short gist of theoretical and empirical studies on different relationships hypothesized in this study.

2.1 *Environmental Kuznets Curve hypothesis*

There are two different streams of research on the link between CO_2e and income in the current literature. Following Kuznets (1955), the first stream concentrations on the impact of profits on environmental contamination, i.e., examining the environmental Kuznets curve (EKC) hypothesis. Meanwhile, the second stream examines the connection between energy consumption and commercial progress by following Kraft and Kraft (1978). In other words, the EKC hypothesis suggests a three-step inverted U-shape curve, i.e., pollution rises with the development of economic activities, reaches a certain level, and decreases after a while. Grossman and Krueger (1991) were the forerunners to test the EKC by empirically testing income/profit-pollution link. Later, Harbaugh, Levinson, and Wilson (2002) indicated differences in past findings are possibly due to the notion that Kuznets's curve may not be effective for all varieties of contaminants. The authors further added that it is suitable for environmental indicators with time and resident effects (e.g., SO_2, NO_x, and CO_2e), rather than those with long-run and indirect effects, e.g., CO_2e, energy use, urban waste, and traffic flows. Based on a meta-analytical study, Dinda (2004) concluded that previous findings have differed because of differences in context ecological standards, implying that the EKC may be context specific. After analyzing the diverse evidence on the EKC hypothesis, Kaika and Zervas (2013) stated energy use/consumption could explain the constructive relationship between CO_2e and income. Regardless, many scholars have used diverse samples, methods, and variables to investigate the interaction between income and CO_2e. For instance, Zoundi (2017) found an increase in per capita enhanced CO_2e in twenty-five African countries during 1980-2011. Using the Autoregressive-distributed lag (ARDL) method, Baek (2015) established marginal support for the EKC hypothesis in Arctic economies during 1960-2010, but economic growth positively influenced environmental quality. Apergis and Ozturk (2015) employed the Gaussian Mixture Model (GMM) technique to test the relationship between income and CO_2e for 1990-2011. The authors validated the EKC hypothesis in fourteen Asian economies. In Fodha and Zaghdoud (2010)'s study, the EKC in Tunisia was confirmed for 1961-2014.

In contrast, Apergis (2016) used CO_2e and the GDP (per capita) to test the EKC hypothesis in the fifteen countries from 1960-2013. Through the Fully Modified Ordinary Least Square (FMOLS) and quantile estimation technique, this study could only confirm the EKC for the twelve out of fifteen countries. Likewise, Özokcu and Özdemir (2017) could not support the EKC hypothesis in twenty-six OECD countries from 1980-2010. Besides, several other studies have also reported the existing of the EKC hypothesis in BRICS (Sebri & Ben-Salha, 2014); 25 OECD member countries (Ben Jebli, Ben Youssef, & Ozturk, 2016); USA (Apergis, Christou, & Gupta, 2017); 20 OECD economies (Churchill et al., 2018); China (Ahmad, Han, Rahman, & Khan, 2018; Ahmad, Rahman, Hong, Khan, Khan, & Khan, 2018); and Pakistan (Rahman & Ahmad, 2019).

2.2 *Renewable energy consumption-CO2e led hypothesis*

Renewable energy has become a crucial factor for the sustainable development of human society. Therefore, policymakers, economists, and environmentalists have frequently asserted the need to promote renewable energy for sustainable growth, green economy, and energy efficiency (Dechezlepretre, & Sato, 2017). Tang, Tan, and Ozturk (2016) indicated energy use/consumption, FDI, and economic development are the chief reasons of CO_2e in the long run. Thus, efforts should be made to promote clean and green technologies among countries and regions. Gielen et al. (2019) argued that renewable energy could meet two-thirds of the global energy demand, contribute meaningfully to reducing greenhouse gas emissions, and help restrict the rising average global surface temperature within two °C from now to 2050.

Of some important studies, Inglesi-Lotz and Dogan (2018), Sugiawan and Managi (2016), and Zoundi (2017) confirmed a statistically significant and negative connection between CO_2e and renewable energy use. Dong et al. (2017) and Bhat (2018) came to a similar conclusion that renewable energy is one of the prime factors mitigating CO_2e BRICS. Another study about economic progress and renewable energy consumption by Sebri and Ben-Salha (2014) established that renewable energy had played an active role in stimulating economic growth in BRICS. Chen, Wang, and Zhangqi (2019) and Shahbaz and Sinha (2018) have reported similar evidence for China and India, respectively. Salim and Rafiq (2012), Boluk and Mert (2015) revealed that renewable energy reduced CO_2e in Turkey, even though Pata (2018) could not support this argument. Acheampong, Adams, and Boateng (2019) observed that CO_2e declined with an increase in renewable energy use in a group of forty-six African countries. Alola, Bekun, and Sarkodie (2019) revealed that environmental sustainability can be improved by renewable energy consumption. Danish, Baloch, Mahmood, and Zhang (2019) reported that although renewable energy was significantly and negatively related to CO_2e in Brazil, India, Russia and China, it was positively and insignificantly related to CO_2e in South Africa. Regardless, numerous researches have confirmed that renewable energy has played an constructive role in environmental improvement (cf. Apergis, Payne, Menyah, & Wolde-Rufael, 2010; Bilgili, Kocak & Bulut, 2016; Dong, Sun, & Hochman, 2017; Ito, 2017; Acheampong et al., 2019; Alola, Bekun, & Sarkodie, 2019; Nguyen & Kakinaka 2019; Sharif, Raza, Ozturk, & Afshan, 2019; Sadorsky, 2009; Pao & Fu, 2013; Destek, 2016; Mert & Boluk, 2016; Armeanu, Vintilă, & Gherghina, 2017; Inglesi-Lotz & Dogan, 2018; REN21, 2018; Zafar, Shahbaz, Hou, & Sinha, 2019; Damette & Marques, 2019; Mert, Boluk & Cağlar, 2019; Bourcet, 2020).

2.3 *The pollution-haven hypothesis*

The pollution haven hypothesis (PHH) is commonly used to explain the relationship between FDI and CO_2e. This hypothesis posits that developing countries import multiple technologies (through FDI) from developed countries. Due to weak environmental policies and low restrictions, the developing economies soon transform into pollution-havens with carbon-intensive technologies that generate high CO_2e (Jain, 2017; Neequaye & Oladi, 2015; Rahman, Ozturk & Zhang 2019b; Khan, Teng & Khan 2019). Even though the past research supports a favorable impact from FDI on economic and financial growth, FDI's environmental effects remain inconclusive and controversial. Past empirical researches have tested the connection of FDI and CO_2e to validate the PHH in different regions or economies, supporting that economic and industrial growth can cause significant CO_2e. Zheng and Sheng (2017) explored [and found support for] a positive relationship between CO_2e and FDI in China from 1997-2009. Behera and Dash (2017) applied the Pedroni cointegration test to explore the link among energy use, urbanization, FDI, and CO_2e in selected seventeen Southeast-Asian countries. The results suggested that FDI and energy use were accountable for increasing CO_2e in those countries. Salahuddin, Alam, Ozturk, and Sohag (2018) examined the link among electricity use, economic development, environment and FDI in Kuwait. The results revealed that FDI increased CO_2e. Koçak and Aykut (2018) analyzed the consequence of FDI on CO_2e in Turkey using the ordinary least-square estimator. The authors concluded that FDI caused an increase in CO_2e in the long run. Sung, Song, and Park (2018) studied the link of FDI and CO_2e in China, and the findings supported that the import of technologies from advanced countries is responsible for the environment damage. Rahman, Cai, Khattak, and Hasan (2019a) examined the connection between remittances, FDI, energy use, and CO_2e for the top-six Asian countries using the ARDL technique, and suppoted FDI predicted CO_2e in India, Sri Lanka, and China. Rahman, Chongbo, and Ahmad (2019) tested the FDI-CO_2e nexus in Pakistan through a nonlinear autoregressive distributed model (NARDL). The result validated an increase in FDI escalated pollution in Pakistan. Sarkodie and Strezov (2019) examined a link among economic development, FDI, energy use, and GHGs for selected Asian economies. The estimates confirmed the PHH for South Africa, Indonesia, India, China, and Iran. Gorus and Aslan (2019) also concluded FDI and energy consumption were primary contributors to environmental damage in the MENA region. In another similar investigation, Khan, Ahmad, Khan (2020) studied the relationship between CO_2e, remittances, income, energy use, and FDI in BRICS from 1986–2016. The results supported that FDI inflows increased CO_2e.

In contrast, some studies have been unsuccessful to validate the PHH. For example, Ssali, Du, Mensah, and Hongo (2019) attempted to link environmental pollution, economic growth, FDI, and energy use in six Sub-Saharan African countries. Still, the authors failed to find any relationship between FDI and CO_2e. Rafique, Li, Larik, and Monaheng (2020) investigated the association between FDI, technological innovation, CO_2e, and financial development in BRICS states from 1990 to 2017. Using the AMG estimator, the results showed that FDI, technological innovation, and financial development upsurged CO_2e. Simultaneously, economic growth, urbanization, energy use, and trade openness increased CO_2e. In another BRICS study, Yilanci, Bozoklu, and Gorus (2020) examined the influence of energy use and FDI inflow on ecological footprint and its components in the long term from 1982–2014. The findings demonstrated that the effect of FDI inflows differed in different countries, where the environmental effect of FDI was positive in India, China, and South Africa, but mixed in Brazil and Russia.

3. CONCEPTUAL MODEL AND THEORETICAL FRAMEWORK

Grounded on the previous studies (Ahmad, Khan, Rahman, Khattak, & Khan, 2019; Goel & Ram, 1994), the following Cobb-Douglas equation was formulated for the interaction between the final output and production factors

$$Y_t = AK_t^{\Theta} L_t^{\rho} I_t^{\xi} \quad (1)$$

Where Y_t = the final output; A = technologies efficiency; K_t = a certain level of capital-output; L_t = a certain level of the labor force; and I_t = innovation activities.

In this study, innovation is assumed as a sub-function of production as it upsurges the capability and efficiency of production in terms of impacting the capital goods (available) levels and affecting talents and skills of workforce inputs. Typically, innovation emerges from continuous research activities and is often classified into two types. First, the green and sustainability-related innovation (GSI) includes research activities that simultaneously generate environmental and productivity benefits. In contrast, the non-green and sustainability-related innovation (NGSRI) are predominantly focused on increasing production efficiency. Assuming that firms engaged in GSI pursue research activities concerning green and sustainable technology (GST), the I_t in Equation (1) was replaced by the green and green and sustainable technology (GST) to obtain the Equation (2) below.

$$Y_t = AK_t^{\Theta} L_t^{\rho} (GSTR_t)^{\xi} \quad (2)$$

For output per capita, Equation (2) was divided by L_t:

$$y_t = Ak_t^{\Theta}(r_t)^{\xi} \tag{3}$$

Where, $y_t = {}^{Y_t}/_{L_t}$, $k_t = {}^{K_t}/_{L_t}$ and $r_t = {}^{GSTR_t}/_{L_t}$

Moreover, it was assumed that not all capital goods were responsible for CO_2e. Past research shows that energy-based-capital goods are the primary sources of environmental degradation. Following the extant approach (cf. Ahmad et al., 2019; Qingquan, Khattak, Ahmad, & Ping, 2020), Equation (3) was converted into the following Equation (4):

$$y_t = AE_t^{\Theta}(r_t)^{\xi} \tag{4}$$

Where, *E* signifies the energy follows in various forms (oil, coal, gas, and renewable). Economists often use economic activities to understand the link between environmental pollution and the economy. May have argued that the global threat to ecological degradation increase with an increase in energy-intensive economic activities. Following the approach used in previous works (e.g., Ahmad et al., 2019; Ahmad & Khattak, 2020), the link between CO_2e and economic activities was formulated as follows.

$$y_t = f(CO2_t) \tag{5}$$

For obtaining the equation for CO_2e, Equation (4) was converted into Equation (5):

$$CO2_t = AE_t^{\Theta}(r_t)^{\xi} \tag{6}$$

Equation (6) above demonstrates that the energy resources and GSTR are predicting CO_2e. The following part, representing the conceptual framework, explains how GSTR affects CO_2e in an economy.

RGST is an essential aspect of the economic growth process. The mechanism that connects RGST to the CO_2e mitigation and the commercial growth process is widely misunderstood. As RGST is considered an integral part of all innovation activities, any innovation activities' fluctuations could affect RGST. Government policies and economic scenarios that have directly and indirectly enhanced RGST and contributed to CO_2e reduction include, but are not limited to, technological innovations from academia in air pollution, water recycling, climate change, and energy efficiency, transmission, distribution, or generation. That said, cyclical fluctuations in an economy is a crucial factor closely linked to these scientific contributions. These fluctuations are characterized by contractionary and expansionary phases in an economy. Typically, the former phase represents shrinkage in GDP, consumer income, industrial production, trade, industrial profits, and employment, while the later phase causes positive improvements in socioeconomic indicators. With a prospering and booming economy, governments can persuade firms to invest in clean technologies using strict environmental regulations. Firms usually allocate financial and other resources to sponsor RGST activities across different sectors. As part of the overall innovation output, scientific patents, papers, and novel ideas originating from universities and research centers contribute to the overall

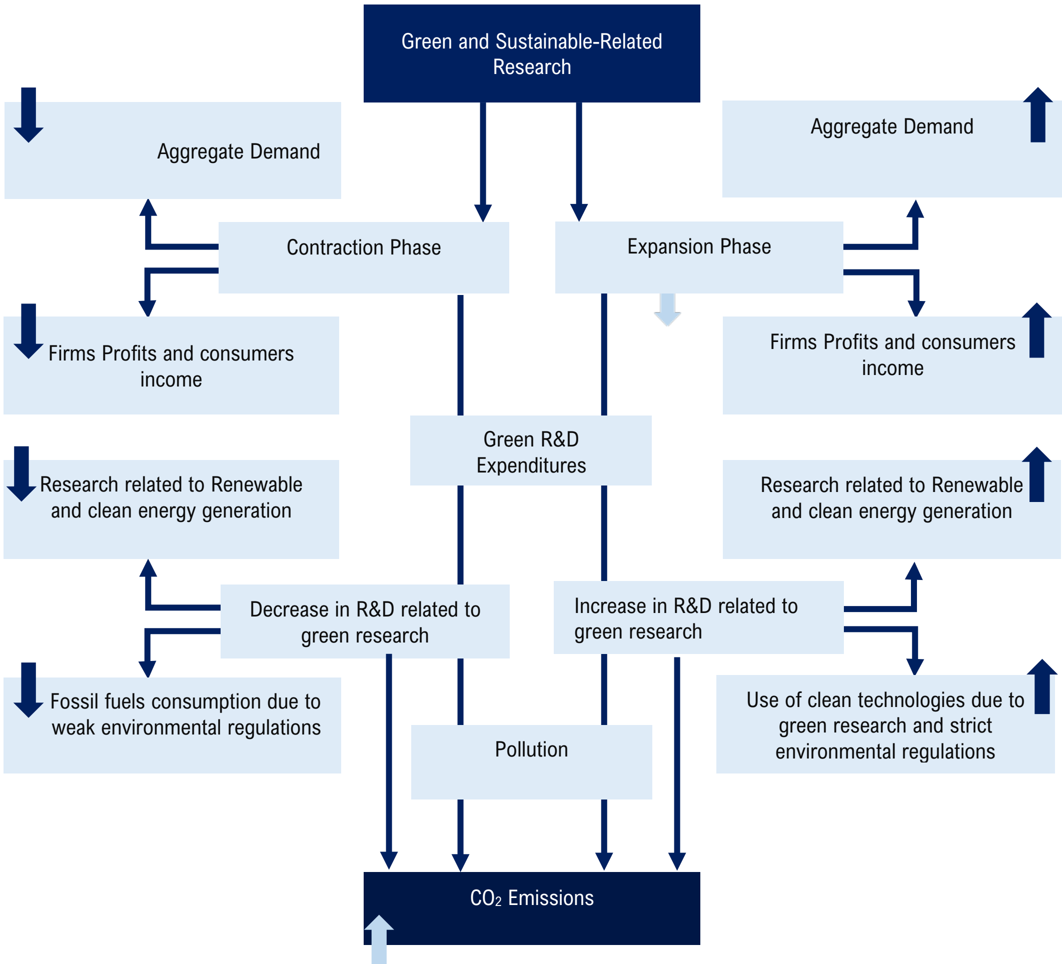

Figure 8. The conceptual framework.

national efforts to curbing CO_2e.

Moreover, monetary policy is another significant factor causing positive shocks in RGST in the economic boom. Policymakers often rely on expansionary monetary policy (reduced interest rates) to gain the investors' confidence during an economic boom (Kouretas & Papadopoulos, 2014) and encourage them to finance RGDT activities. Himmelberg and Petersen (1994) asserted that innovation and R&D activities, whether non-RGST or RGST, might be procyclical because of the liquidity effects. The authors explained that a rise in the money supply could cause a decline in the interest rates, leading to a rise in innovation activities (RGST and GR&D), which could help to mitigate CO_2e. Alternatively, policymakers also use expansionary fiscal policy to encourage commercial investment in RGST activities. With reduced indirect and direct tax, investors have more funds to promote innovation activities in academia and beyond.

In contrast to the expansionary periods, the contraction periods follow a decline in socioeconomic indicators, including, GDP, trade, income, employment, aggregate demand, and education funding. Both the private and public sectors suffer, in terms of profit, earnings, and revenues. In this situation, the enforcement and implementation of environmental regulations are kept weak to encourage economic activities. As a result, the commercial sectors use carbon-intensive fossil-fuels to produce cheap products. The RGST funding and expenditure decline as firms have limited resources to spare for green technologies. An over-reliance on non-renewable energy, processes, and technologies for cheap production enhances the possibility of high CO_2e.

Therefore, the following parametrical restriction was imposed to capture the RGST shocks (both positive and negative) in the CO_2e equation, endogenously.

$$\chi = \begin{cases} \xi^{+} & if\ \Delta r_t > 0 \\ \xi^{-} & if\ \Delta r_t > 0 \end{cases} \tag{7}$$

Where, ξ^{+} = positive RGST shocks and ξ^{-} = negative RGST shocks. The former shock shows the positive shift in green and sustainable research activities driven by an economic boom, while the negative shock of green and sustainable research activities due to a decline in economic activities recession. These shifts and changes in GSTR variables are depicted in Equation (8) below.

$$CO2_t = AE_t^{\theta}(I(\Delta r_t > 0)\Delta r_i)^{\xi +}\ (I(\Delta r_t < 0)\Delta r_i)^{\xi -} \tag{8}$$

Where the identity function $(I(\Delta r_t > 0)\Delta r_i)^{\xi +}$ and $(I(\Delta r_t < 0)\Delta r_i)^{\xi -}$ can be expressed as follows:

$$I(\Delta r_t > 0) = \begin{cases} 1 & if\ \ \Delta r_t > 0 \\ 0 & if\ \ \Delta r_t < 0 \end{cases} \tag{9}$$

$$I(\Delta r_t < 0) = \begin{cases} 0 & if \ \Delta r_t > 0 \\ 1 & if \ \Delta r_t < 0 \end{cases} \qquad (10)$$

Following the method adopted in past studies (Ahmad, Khan, Rahman, Khattak, et al., 2019; Qingquan et al., 2020; Schorderet et al., 2003; Shin et al., 2014), the two GSTR components (positive and negative) can be written as:

$$CO2_t = AE_t^{\Theta}(r_t)^{\xi^+}(r_t)^{\xi^-} \qquad (11)$$

Assuming that other factors are also potential determinants of CO_2e, this study incorporated exports (EXP), GDP per capita, and FDI into the model for the following reasons. Firstly, BRICS states are among the most attractive global destinations for FDI because of relatively flexible environmental regulations. Many studies have shown that though technology transfers (led by FDI) can positively affect economic development, its role on environmental damage could be both positive and negative. Secondly, these economies are currently at the forefront of industrial production. The production of goods exceeds local demands in most developing economies so that the surplus stock is used for foreign exports. An increase in demand offers an incentive for producers to manufacture goods at lower costs. This increases the use of fossil-fuels for price competitiveness in global markets and energy-intensive production; consequently, increasing the level of CO_2e. Therefore, it is rational to speculate that exports may increase CO_2e. Thirdly, the BRICS states have shown impressive GDP figures compared to other emerging economies in the past few decades. As per the EKC hypothesis, pollution follows an upward trend in the early phases of economic growth. As the BRICS states are in the initial economic development stages, the pollution is expected to follow an upward trend until the threshold is reached. After including the three essential factors in Equation (11), the following equation was obtained.

$$CO2_t = AY_t^{\delta}FDI_t^{\Gamma}EXP_t^{\eta}E_t^{\Theta}(r_t)^{\xi^+}(r_t)^{\xi^-} \qquad (12)$$

Energy consumption is considered an essential driver of economic progress. Using different econometric methods, many scholars have demonstrated that energy production and consumption are the leading elements of climate change and pollution. Researchers have empirically validated this argument for many regions and countries (Rehman & Rashid, 2017). Recent works by Itkonen (2012) and Jaforullah and King (2017) suggested a combination of CO_2 and energy use can lead to bias results, model spuriousness, inconsistent findings. As seen in Equation (13), the energy consumption variable was replaced by energy use (*E*) by renewable energy consumption (REC), as per Ahmad et al. (2019).

$$CO2_t = AY_t^{\delta}FDI_t^{\Gamma}EXP_t^{\eta}REC_t^{\Theta}(r_t)^{\xi^+}(r_t)^{\xi^-} \qquad (13)$$

Where: CO_2e= Carbon dioxide emissions; Y= GDP (per capita); EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment;

GSTR= Green and sustainable technology research.

4. METHODOLOGY

4.2 *Data sources and variables*

The data were gathered from various sources, including World Bank Indicators, Incites (Web of Science), and OECD database. The data were analyzed for the period 1990-2018. First, Table 1 presents a detailed description of all variables, units of measurements, data sources, and expected signs.

Table 1. Data sources and variables.

Variables	Measurement unit	Source	Expected signs
CO_2e	Metric tons of CO_2e	World Bank (2020)	
Y	Constant USD, 2010	Word Development Indicators (WDI, 2019) https://databank.worldbank.org/source/world-development-indicators#advancedDownloadOptions	Positive
EXP	Percentage of GDP	World Bank (2020)	Positive
REC	Percentage of total final energy use	World Bank (2020)	Negative
FDI	BoP, current US$	World Bank (2020)	Positive
GSTR	Number of scientific publications	InCites Database, Clarivate Analytics Web of Science (Incites 2020) https://incites.clarivate.com/#/explore/0/region	Negative

Note. Abbreviations: CO_2e= Carbon dioxide emissions; Y= GDP; EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment; RGST= Green and sustainable technology research.

4.3 *Econometric techniques*

4.3.1 Unit-root testing

The study first analysed data by cross-sectional dependence (CD) among all units. Testing CD before the unit-root testing procedure is useful in identifying the appropriate and specific unit-roots tests (1st, 2nd, and 3rd generation) to address CD in the data series. A vast array of global and regional factors, including but not limited to globalization, economic integration, financial crisis, recessions, changes in oil prices, various common stocks, omitted common factors (observed/unobserved), and residual interdependence, are linked to CD. The CD problem must be addressed as underestimating this issue may lead to spurious results and bias (Salim, Yao, & Chen 2017). And the presence of CD was checked using the M Hashem Pesaran (2015)'s CD test. After examining the CD test outcomes, the second phase of analysis included unit-root testing or testing potential stationarity in the panel data.

Past literature offers three different stationarity testing methods (first, second, and third-generation unit-root tests) classified based on various statistical problems dealt with by each method. For instance, the unit-root methods proposed by Choi (2001), and Levin, Lin, and Chu (2002) are considered suitable for testing non-stationarity problems in homogenous panels. Unit-root test is commonly used for heterogeneous panels (Im, Pesaran & Shin 2003). Second, the Lluís Carrion-i-Silvestre, Del Barrio-Castro, and López-Bazo (2005)'s unit-root test effectively addresses the problems of multiple structural breaks, though it remains inappropriate to address CD. Contrary to the first-generation unit-root tests of Maddala and Wu (1999) and Levin, Lin and Chu (2002), the second-generation panel unit-root tests introduced by Pesaran (2007) and Choi (2006) efficiently deal with heterogeneity and CD issues. That said, a pertinent concern is that both the first and second-generation tests may prove to be inefficient and powerless considering potential structural breaks in the panel data because of global or local events. Even though most researchers currently rely on either first or second-generation unit-root tests, the third-generation tests are superior to prior methods in addressing potential issues in the data concerning the CD, heterogeneity, and structural breaks (Bai & Carrion-I-Silvestre, 2009). For robustness, this study adopted the third-generation Bai and Carrion-I-Silvestre (2009) (BCIST) and Pesaran (2007) (PURT) unit-root tests to address the problem of non-stationarity (with CD). The CD presence does not allow for conducting the first-generation panel unit root test (Jalil, 2014).

4.3.2 Cointegration testing

The next step was to examine potential slope heterogeneity/homogeneity in the data. This paper applied the Pesaran and Yamagata's (2008) slope homogeneity tests, a more modified version of Swamy's (1970) test. This test estimates two hypotheses for the slope perimeters: null hypothesis (homogeneity) vs. alternate hypothesis (heterogeneity). An issue with the first-generation cointegration tests (i.e., Larsson, Lyhagen, & Löthgren, 2001; Mccoskey & Kao, 1998; Pedroni, 2004; Westerlund, 2005) is that they cannot produce robust results CD and distortion of size properties. Other alternate methods (i.e., Kao, Chiang, & Chen, 1999; Pedroni, 2001) are equally inefficient as they follow the assumption that no CD exists in the cross-sections. The study applied heterogeneous assessment methods considering potential CD, non-stationarity, and heterogeneity problems in the data. The BCSPC (Banerjee & Carrion-i-Silvestre, 2017) and WEPC (Westerlund & Edgerton, 2008) can effectively deal with cointegration in the presence of structural breaks. Even though Westerlund's (2007) method tackles CD and heterogenous slope perimeter issues, it fails to capture the impact of potential structural breaks. This problem may disrupt the rejection of null hypothesis. The third-generation cointegration test used in this study is better than the first and second generation, in terms of dealing with slope heterogeneity, CD, serially correlated errors, and potential structural breaks across diverse places in each cross-section. In addition to the above, the current study used corroborated the results with another Banerjee and Carrion-i-Silvestre (2017) cointegration testing method, which is built on the common correlated effects mean group (CCEMG) method. Despite a spurious regression framework, this technique enables estimation of robust results with both weak and strong CD, heterogeneity, non-stationarity, and parameters in the panel data.

4.3.3 Cross-sectionally augmented autoregressive distributed lags (CS-ARDL)

Previously, scholars have frequently identified different factors that can act as common shocks (e.g., financial crises, oil prices, and regime change). These shocks tend to generate CD problems in the data, which may result in spurious results. This can become more problematic when the regressors in the model are correlated with the unobserved common factors. If CD and slope heterogeneity arise, the CS-ARDL can prove to be the most appropriate estimation tool, given that it applies the dynamic common correlated effects estimator to address such problems (Çoban & Topcu, 2013; Yao, Ivanovski, Inekwe & Smyth, 2019). Below, Equation (1) presents the basic equation for the CS-ARDL estimation, representing the autoregressive distributed lags (ARDL) model.

$$W_{i,t} = \sum_{I=0}^{P_W} \gamma_{I,i} W_{i,t} - 1 + \sum_{I=0}^{P_Z} \beta_{I,i} Z_{i,t-1} + \varepsilon_{i,t} \tag{1}$$

With the potential CD in the data, Equation (1) could lead to spurious results. By extension of Equation (1) through the cross-section's averages of each regressor, Equation (2) was obtained. This procedure can help overwhelm the unfitting implications related to the presence of the threshold effect generated by CD (Chudik & Pesaran, 2015).

$$W_{i,t} = \sum_{I=0}^{P_W} \gamma_{I,i} W_{i,t} - 1 + \sum_{I=0}^{P_Z} \beta_{I,i} Z_{i,t-1} + \sum_{I=0}^{P_X} \grave{\alpha_i}, I\bar{X}_{t-1} + \varepsilon_{i,t} \tag{2}$$

Where: $\bar{X}_{t-1}$ = (W_(i.t-1))̅,(Z_(i.t-1))̅) = the dependent variable and independent variables (averages) under study; P_w, P_z, and P_x = lags for each variable; $W_{i,t}$ refers to the dependent variable (i.e., CO_2e); and $Z_{i,t-1}$ = independent variables, i.e., REC, EXP, FDI, GDP, GSTR (positive shocks), and GSTR (negative shocks); and $\bar{X}_{t-1}$ = the averages of cross-section (not just the inclusion of trends or time dummies) as to limit CD generated by the effects of spillover (Liddle, 2018). Moreover, the CS-ARDL estimates were aimed at the long-term coefficients from the short-term coefficients. The long-term coefficient and mean group estimator are set as:

$$\hat{\pi}_{CS-ARDL,i} = \frac{\sum_{I=0}^{pz} \hat{\beta}_{I,i}}{1 - \sum_{I=0}^{pw} \widehat{\gamma_{I,\imath}}} \tag{3}$$

The mean group is set as:

$$\hat{\hat{\pi}}_{MG} = \frac{1}{N} \sum_{I=0}^{P_W} \hat{\pi}_i \tag{4}$$

Short-run Coefficients are assessed by:

$$\Delta W_{i,t} = \vartheta_i\left[W_{i,t-1} - \pi_i Z_{i,t}\right] - \sum_{I=1}^{P_W-1} \gamma_{I,i}\, \Delta_I W_{i,t-1} + \sum_{I=0}^{P_Z} \beta_{I,i}\, \Delta_I Z_{i,t}$$
$$+ \sum_{I=0}^{P_x} \grave{\alpha_i}, I\bar{X}_t + \varepsilon_{i,t} \quad (5)$$

Where Δ_I=t-(t-1)

$$\hat{\tau}_i = -\left(1 - \sum_{I=1}^{pw} \widehat{\gamma_{I,\iota}}\right) \quad (6)$$

$$\hat{\pi}_i = \frac{\sum_{I=0}^{pz} \hat{\beta}_{1,i}}{\hat{\tau}_i} \quad (7)$$

$$\hat{\hat{\pi}}_{MG} = \frac{1}{N}\sum_{i=1}^{N} \hat{\pi}_i \quad (8)$$

The error correction mechanism (ECM (−1)) for CS-ARDL (similar to pooled mean group) shows the adjustment speed to equilibrium or the time an economy needs to arrive at the equilibrium point.

4.3.4 Robustness check

Compared to slope heterogeneity (SH) and CD, the traditional approaches may offer biased estimations and findings (Çoban & Topcu, 2013; Yao et al., 2019). Considering CD, SH, and structural breaks, the Augmented Mean Group (AMG) estimator presented by Eberhardt and Teal (2010) was used. Even with the non-stationarity and unobserved common factors, the CCEMG performs better for assessment. The AMG method deals with heterogeneity, CD, and structural breaks and includes year dummies. It treats the unobservable factor as a common dynamic process (Eberhardt & Teal, 2010; Z. Khan et al., 2020) , not as a nuisance. After establishing long-run relationships among all variables, the FMOLS method (Pedroni, 2000) was also applied to check the country-wise relationship. The Panel FMOLS (PFMOLS) are superior in that they allow for serial correlation (SC), the existence of endogeneity, and cross-sectional heterogeneity (Gaol, 2015).

5. RESULTS AND DISCUSSION

5.1 *Unit-roots and slope homo/heterogeneity testing*

Before examining the determinants of CO_2e, the panel data was checked for possible issues, e.g., unit-root, heterogeneity, serial-correlations. The following section presents a discussion on the results of various econometric tests used in this study. To begin with, Table 2 explains the results of the SHT and CSI tests. The SHT (Δ̃_adjusted and Δ̃) and CSI (at one percent significance level) confirmed the null hypothesis's rejection. These results suggested that any shocks (positive or negative) to FDI, REC, EXP, RGST, Y, and CO_2e in one economy within the selected group will also affect other group members, i.e., all BRICS members were interdependent. In the second step, tests were conducted to examine all data's the unit-root, structural break, integration order, and stationarity.

Table 2. The SHT and CSI test results.

Slope Heterogeneity/Homogeneity Test	$CO_{2,it} = f(Y_{it}, Y_{it}^2, RGST_{it}^+, RGST_{it}^-, REC_{it}, EXP_{it}, FDI_{it})$			
	$\tilde{\Delta}$ − **Value**	P-Value	$\tilde{\Delta}_{\textbf{Adjusted}}$ − **Value**	P-Value
	8.039***	0.000	9.680***	0.000

Cross-Section Independence/Dependence Test

Variable(s)	Statistic	P-Value	Mean ρ	Abs mean ρ
$CO_{2,it}$	5.751***	0.000	0.34	0.80
Y_{it}	15.332***	0.000	0.90	0.90
EXP_{it}	16.207***	0.000	0.95	0.95
REC_{it}	5.749***	0.000	0.34	0.45
FDI_{it}	11.972***	0.000	0.70	0.70
$RGST_{it}$	16.232***	0.000	0.95	0.95

Note. Abbreviations: CO_2e= Carbon dioxide emissions; Y= GDP; EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment; RGST= Green and sustainable technology research. Asterisks (*) are for level of significance, i.e., 1%, 5% & 10% with ***, ** and *, respectively.

Table 3 exhibits the PURT outputs. This test revealed that CO_2e, EXP, and RGST converted from non-stationary to stationary at the first difference, whereas REC and FDI remained stationary. This test failed to deliver structural breaks' information. Structural breaks offer critical information about the shifts that have occurred in different global economies. As the PURT ignores structural breaks, it inhibits the possibility of producing bias and spurious results. Thus, the BCIST was conducted to solve this econometric issue. This technique permits several structural breaks in the data.

Table 3. The unit-root test results: PURT.

Variables	Level (I(0))		1st Difference (I(1))		Integration Order
	No Trend	With Trend	No Trend	With Trend	
$CO_{2,it}$	-2.170	-1.330	-3.562***	-3.976***	I(1)
Y_{it}	-1.817	-1.417	-2.860***	-3.411***	I(1)
EXP_{it}	-1.339	-2.743*	-4.915***	-5.085***	I(1)
REC_{it}	-3.057***	-2.986**	-	-	I(0)
FDI_{it}	-2.603***	-2.902***	-	-	I(0)
$RGST_{it}$	-2.118	-2.471	-5.938***	-6.052***	I(1)

Note. Abbreviations: CO_2e= Carbon dioxide emissions; Y= GDP; EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment; RGST= Green and sustainable technology research. Asterisks (*) are for level of significance, i.e., 1%, 5% & 10% with ***, ** & *, respectively.

Table 4 demonstrated all variables converted from non-stationary to stationary at the first difference in front of structural breaks, thereby permitting the CSR-ARDL technique. More so, all the selected variables had the same order of integration. An inquiry into the break years (BCIST) offered some interesting insight into important events in the BRICS states. In 1997, an economic crisis that originated from Thailand extended to other economies in Asia. Many of these affected economies purchased the US treasury bonds and adopted strict protectionist policies to prevent a financial catastrophe in their respective countries (Schwab et al., 2000). The global social and economic landscape was greatly affected by several events that happened afterward: the energy crisis (the 2000s); the Global Recession (2007-2008); the Russian Economic Crisis (2008-2009); the Chinese Stock Market Crash (2015-2016); and the Brazilian Financial Crisis (2017-18). These historical events impacted several socioeconomic factors in the BRICS economies, including CO_2e, Y, EXP, REC, FDI, and RGSTR.

Table 4. The unit-root test results: BCIST

Variables	Z	Pm	Pa	Structural Breaks
Level (I(0))				
$CO_{2,it}$	-1.038	1.42*	16.37	2016-1997-2001
Y_{it}	1.004	-0.805	6.39	2001-2007-2014
EXP_{it}	-0.828	0.096	10.43	2003-2008-2010
REC_{it}	-1.303*	0.938	14.19	2013-2016-2000
FDI_{it}	-1.596*	2.15**	19.61	1994-2001-2004
$GSTR_{it}$	-0.572	-0.594	7.342	2004-2010-2013
1st difference (I(1))				
$\Delta CO_{2,it}$	1.81**	4.10***	28.36	-
ΔY_{it}	1.80**	1.36*	46.52*	-
ΔEXP_{it}	-1.73**	6.83***	45.21*	-
ΔREC_{it}	-2.18**	14.22***	73.59***	-
ΔFDI_{it}	-1.83**	4.36***	49.52**	-
$\Delta GSTR_{it}$	-1.92**	6.82***	47.71*	-

Note. Abbreviations: CO_2e= Carbon dioxide emissions; Y= GDP; EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment; RGST= Green and sustainable technology research. Critical values (CV) for Z and Pm is 2.326, 1.645, 2.282 & 56.06, 48.60 and 44.90 for P.

5.2 *Panel cointegration testing*

Table 5 depicts the panel cointegrations tests' results. First, the BCSPCT validated the presence of a long-run association among all selected variables. While accounting for the existence of endogenous regressors, heterogeneous breaks (unknown timing), and serial-correlation, all of the WEPCT test statistics (with structural breaks) were found to be significant at one percent, i.e., the null hypothesis was not accepted. In short, both the WEPCT and the BCSPCT offered empirical support for the cointegration relationships among variables.

Table 5. The panel cointegration tests results: BCSPCT & WEPCT.

Countries\Model		With Constant	With Trend	Non-Deterministic Specification
BCSPCT				
Full sample		-2.70**	-4.27**	-4.30**
Cross-Sections and Full Sample Cointegration	Brazil	-3.37**	-4.94**	-6.08**
	Russia	-2.54**	-2.60**	-2.42**
	India	-4.41**	-5.69**	-6.26**
	China	-2.44**	-3.48**	-2.76**
	South Africa	-7.59**	-4.61**	-3.98**
WEPCT with structural breaks				
Statistic		$Z(N)^{\varphi}$ (P-Values)	$Z(N)^{\tau}$ (P-Values)	Structural Breaks
No Break		-4.17*** (0.000)	-4.01*** (0.000)	-
Mean Shift		-3.47*** (0.000)	-3.41*** (0.000)	2001-1997-2014
Regime Shift		-3.58*** (0.000)	-3.39*** (0.000)	1997-2004-2007

Note. The critical values (CV) for 5% & 10% for constant is -2.32, -2.18, and for trend is -2.92 & -2.82.

5.3 *Short- and long-run estimations*

Table 6 shows the outcomes of estimations (long and short run). Some key findings are discussed hereafter. First, the CS-ARDL estimates indicated that a significant negative relationship existed between RGST (positive shocks) and CO_2e in BRICS states—a one percent upsurge in RGST predicted a decline in CO_2e by 0.24 (long run) and 0.19 percent (short run). This implied that policies, initiatives, economic scenarios that encourage RGST have effectively mitigated environmental pollution in the BRICS economies. A feasible explanation is that investors, governments, and academic institutions have more budget and funds to spare for conducting RGST and R&D during economic booms, which are characterized by an increase in profits, income, industrial growth, employment, and exports (Zheng, Song, Zhang, et al., 2018). In the past three decades, there has been a paralleled progress in innovation, per capita income, global trade among BRICS states. In China, massive economic expansion, urban development, power generation plants, and large-scale industrialization have contaminated air, soil, and water. Facing global and local pressure, the BRICS states have collaborated to address these ecological issues through partnerships and investment in green R&D at the academic, government, and enterprise levels. From 1990 to 2016, green and sustainable technologies in China, India, Russia, and Brazil increased by 22, 15, 14, 8 percent, respectively. South Africa, however, lagged in the race towards a green economy, where the increase was reported at -0.27 percent. At *prime facia*, it seems that China is making swift progress in the number of eco-related patents, innovations, publications, and funding than other members in the BRICS group. In China, both public and private sectors are funding green projects and participating in the development of projects related to wind, clean coal, hydro, and solar energy. Some tech companies, including Baidu, Chindata, GDS, and Alibaba have even installed wind and solar energy-based generators to power their data centers[1]. If this situation continues, a constant supply of eco-patents and innovations in renewable energy and sustainable technologies can help the BRICS economies to achieve energy efficiency and reduce toxic emissions and waste. For effective CO_2e mitigation, these economies need to: focus on research and science; commercialize eco-innovation; advance technologies for general purposes (e.g., biotechnology, nanotechnology, and ICT); widely disseminate and diffuse green technologies, knowledge, standards, skills, and processes; develop new markets for green and sustainable innovations; and articulate new green economy models.

Table 6. The short- and long-run estimations results: CS-ARDL technique.

Variables	Coefficients	Standard Error	Z-Statistic	P-Values
Short-run estimations				
ΔY_{it}	0.80***	0.220	3.64	0.000
ΔY_{it} – Squared	-0.031***	0.011	-2.87	0.004
ΔEXP_{it}	0.12*	0.066	1.84	0.066
ΔREC_{it}	-0.21*	0.109	-1.92	0.054
ΔFDI_{it}	0.22**	0.101	2.20	0.027
$\Delta RGST^{+}_{it}$	-0.19**	0.085	-2.29	0.022
$\Delta RGST^{-}_{it}$	0.011**	0.004	2.50	0.012
$ECM_{(-1)}$	-0.81***	0.179	-4.53	0.000
Long-run estimations				
ΔYit	0.95***	0.224	4.24	0.000
ΔYit – Squared	-0.043**	0.018	-2.38	0.017
ΔEXP_{it}	0.16**	0.069	2.40	0.016
ΔREC_{it}	-0.43***	0.122	-3.54	0.000
$\Delta FDIit$	0.25**	0.083	3.01	0.002
$\Delta RGST^{+}_{it}$	-0.24***	0.064	-3.75	0.000
$\Delta RGST^{-}_{it}$	0.016***	0.005	3.20	0.001

Note. Abbreviations: CO_2e= Carbon dioxide emissions; Y= GDP; EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment; RGST= Green and sustainable technology research.

Second, the results depicted a significant and positive interaction between CO_2e and RGST (adverse shocks). As the CO_2e declining by 0.011 (short-run)

[1] https://www.scmp.com/news/china/politics/article/3045616/china-tech-giants-wake-renewable-energy-fossil-fuels-still

and 0.016 percent (long-run) with one percent increase in RGST, it was concluded that policies, economic conditions, and strategies discouraging RGST had contributed to CO_2e in the BRICS economies. A rational explanation for this finding resides in the notion that investors, governments, and educational institutions have little or no funds to spare for RGST during recessions and contractions. Reason being, these economic situations are often characterized by a decline in industrial production, aggregate demand, employment, income per capita, and exports. With private and public sponsors reluctant to fund R&D, academic institutions withdraw support and incentives to conduct RGST. Governments are also keen to enhance the confidence of investors and businesses by relaxing environmental restrictions and regulations. Rather than seeking clean fuel and production alternatives, companies use dirty technologies and fuel to save costs, which causes ecological damage (Ahmad, Khan, Rahman, Khattak, et al., 2019). Another important consideration is that increasing export duties and interest rates may trigger a negative shock in RGST. In short, the real data of China, India, Russia, Brazil, and South Africa also supported that pro-cyclical patterns existed between RGST and CO_2e.

Third, the results suggested that exports and CO_2e are negatively associated—one percent upsurge in exports caused a rise in CO_2e by 0.12 (short-run) and 0.16 percent (long-run). This result implied the enhanced need for export goods had motivated firms to produce cheaper goods at low prices using dirty technologies to meet the global demand; consequently, enhancing CO_2e. This finding supported previous works for middle-income economies (Lv & Xu, 2019); China (Michieka et al., 2013); OECD (Ahmad, Khan, Rahman, Khattak, et al., 2019); and South Africa (Ahmad & Khattak, 2020). Fourth, the estimates revealed a significant and negative connection between CO_2e and FDI—one percent increase in FDI caused an upsurge in CO_2e by .22 (short run) and .25 (long run) percent. Besides confirming the PHH in BRICS economies, this result suggested that the influx of FDI has had an adverse consequence on BRICS' environment quality. Moreover, the presence of flexible and weak environmental policies created a favorable atmosphere for carbon-intensive technologies and industries to dwell for long, converting these emerging nations into pollution hotspots. Regardless, this finding is similar to studies carried out for BRICS (Z. U. Khan et al., 2020); Asian countries (M. A. Khan & Ozturk, 2020); MIKTA states (Bakirtas & Cetin, 2017); ASEAN (Guzel & Okumus, 2020). This finding is, however, inconsistent with prior works for Turkey (Mert & Caglar, 2020); Kyoto Annex countries (Mert & Bölük, 2016); China (Hao, Wu, Wu, & Ren, 2020). Finally, the results also supported that REC has played an important role in reducing CO_2e—the EKC hypothesis accepted.

5.4 *Robustness check*

The robustness and consistency of all estimates were tested using the AMG and PFMLOS. Table 7 and 8 exhibited that all the CS-ARDL estimates were robust. The results were similar to the coefficient and signs of all the selected variables in the AMG and PFMLOS outputs.

Table 7. Results of robustness testing: AMG

Variables	Coefficients	Standard Error	P-Values
Y_{it}	0.89***	0.304	0.003
Y_{it} – Squarred	-0.026***	0.0069	0.000
EXP_{it}	0.16*	0.089	0.071
REC_{it}	-0.14**	0.067	0.035
FDI_{it}	0.21**	0.083	0.010
$GSTR^{+}_{it}$	-0.21***	0.014	0.000
$GSTR^{-}_{it}$	0.12**	0.059	0.035
Intercept	1.24**	0.586	0.034
Wald-Test	376.94***		0.000

Note: Asterisks (*) are for level of significance, i.e., 1%, 5% & 10% with ***, ** & *, respectively. Abbreviations: CO_2e= Carbon dioxide emissions; Y= GDP; EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment; GSTR= Green and sustainable technology research

Table 8. Country-based coefficients using FMOLS

Variables	Brazil	Russia	India	China	South Africa
Y_{it}	0.83**	0.79***	0.87***	0.96***	0.80***
Y_{it} – Squarred	-0.021***	-0.026*	-0.016***	-0.043**	-0.014***
EXP_{it}	0.17**	0.23**	0.29***	0.36***	0.21***
REC_{it}	-0.43***	-0.13*	-0.17***	-0.27**	-0.16*
FDI_{it}	0.21***	0.108*	0.24**	0.31***	0.11**
$RGST^{+}_{it}$	-0.024*	-0.017**	-0.027**	-0.141**	-0.018**
$RGST^{-}_{it}$	0.067*	0.056**	0.041**	0.076**	0.029***

Note: Asterisks (*) are for level of significance, i.e., 1%, 5% & 10% with ***, ** & *, respectively. Abbreviations: CO_2e= Carbon dioxide emissions; Y= GDP; EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment; GSTR= Green and sustainable technology research

5.5 *Causality testing*

Table 9 displays the causality testing (DHPCT)'s results. The results revealed a two-way causality run from Y, REC, FDI, EXP, RGST (positive), and RGST (negative) to CO_2e. These results indicated that policies focused on increasing or decreasing Y, REC, FDI, EXP, RGST (positive), RGST (negative) had decreased or increased CO_2e, directly and indirectly.

Table 9. Dumitrescu-Hurlin-2012 (Heterogeneous) panel causality

Null Hypothesis	W-Stat.	Zbar-Stat.	Prob.
LY → LCO_2e	5.90***	3.40	0.000
LCO_2e → LY	11.81***	8.84	0.000
LY-Squared → LCO_2e	5.54***	3.07	0.002
LCO_2e → LY-Squared	11.42***	8.47	0.000
LREC → LCO_2e	6.89***	4.31	0.000

$LCO_2e \rightarrow LREC$	4.59***	2.19	0.027
$LFDI \rightarrow LCO_2e$	6.08***	4.02	0.000
$LCO_2e \rightarrow LFDI$	1.03	1.40	0.342
$LEXP \rightarrow LCO_2e$	5.86***	3.37	0.000
$LCO_2e \rightarrow LEXP$	9.71***	6.90	0.000
$RGST\_P \rightarrow LCO_2e$	6.26***	3.74	0.000
$LCO_2e \rightarrow RGST\_P$	5.17***	2.73	0.006
$RGST\ \_N \rightarrow LCO_2e$	6.51***	3.21	0.000
$LCO_2e \rightarrow RGST\_N$	2.88	0.62	0.529

Note: Asterisks (*) are for level of significance, i.e., 1%, 5% & 10% with ***, ** & *, respectively. Abbreviations: CO2e= Carbon dioxide emissions; Y= GDP; EXP= Exports; REC= Renewable energy consumption; FDI= Foreign direct investment; GSTR= Green and sustainable technology research

6. CONCLUSION AND POLICY RECOMMENDATIONS

A primary target of this research was to test the potential impact of all shocks (positive and negative) in RGST on environmental pollution in BRICS states from 1990-2018 with use empirical evidence. A summary of the results of various econometric tests conducted in this study is presented as follows. First, the cointegration test results (BCSPCT and WEPCT) recognised a long-term relationship among all selected variables. Second, the estimations (short- and long-run) through the CS-ARDL estimator revealed that REC and RGST (positive shocks) had a mitigating influence on environmental pollution. In contrast, EXP, Y, FDI, RGST (negative shocks) had facilitated environmental pollution in BRICS economies. The robustness of these results was further validated by the AMG and PFMOLS outputs. Simultaneously, the causality testing revealed that CO_2e had a two-way causal relationship with all the other selected variables.

This study has drawn the following vital policy implications. First, the current findings assert the need for considering the cyclicality of RGST before designing and implementing policies. With the positive shocks in RGST showing a favorable environmental impact, policymakers in the BRICS group should introduce policies that encourage investors, academia, and independent sponsors to support RGST during the four economic scenarios to ensure long-term sustainable development. Member nations should initiate inter and intra-group programs and projects to stimulate the capacity of RGST, eco-innovation, and green technologies. This should include funding and support guidelines for all sponsoring agencies, e.g., academia and financial institutions. In other words, these policies should pave the way for a green economy, sustainable development, and RGST at the regional and local levels. The inter-group collaborative efforts should focus on: shared promotion of technology, science, RGST, and education; identifying and controlling factors that limit the access of investors, academia, and independent sponsors to green funding; providing support and incentives to interested agencies facing high administrative costs and financial burdens; and on encouraging the RGST and academic-led eco-patent development through the adoption of ICT across private and public sectors. However, policymakers should ensure that these new policies are intertwined with the overall policies concerning ICT, science, technology, and innovation. That said, it remains critical that the implementation and monitoring of these policies are carried out through a fair and transparent system to restrict fraud, corruption, and funds embezzlement. Each member state should offer a fair opportunity to new entrants and existing players, while simultaneously sponsoring young researchers and talent in the academia to contribute to the development of eco-related research and patents.

Second, the present findings require the need for enhancing the absorption capacity, research, and scientific standards of the academic, public sector, and industrial institutions of the BRICS states. This will serve as a catalyst for eco-related innovation activities during booms and recessions. Therefore, these economies should take advantage of their funds, infrastructure, and natural resources to cultivate capacity. This initiative can potentially serve as a starting point for integrating the 'green perspective' into infrastructure, business, public sector, and academia. Leaders, especially educational, should acknowledge and disseminate the importance of RGST and education as a key determinant of the green economy within their respective countries, regions, and institutions. By aligning the goals with the SDGs, these initiatives can yield far-reaching results. Policymakers are expected to initiate educational policies that encourage academic institutions to divert sufficient financial and other resources to set up separate department and innovation centers for researching green economy models, green technology, energy efficiency, and environmental preservation. Specific incentives, rewards, and bonus schemes should be introduced to attract return-home, foreign, and local talent. The BRICS states can learn from China's '1000 Talents Program' to attract talent in their respective countries. To summarize, the BRICS state should use shared intellectual property and green resources to increase the institutional capacities at home countries to gain the competencies and skills required for green transformation.

Third, the current results revealed that economic downturns adversely affect RGST, which indirectly enhances CO_2e. Provided that eco-innovation entails high costs, lack of funding, and low potential and capacity of enterprises, policymakers in immature markets among the BRICS states should develop comprehensive risk-assessment and support systems for green investors by forming intellectuals and experts from BRICS states and other developed economies. So the social entrepreneurs and investors can support RGST and GST development within academia and beyond during the four economic cycles. Fourth, the validation of the PHH in the present context supports prior views that ineffective and weak regulation, coupled with the inflow of carbon-intensive production through FDI, have changed developing economies into pollution havens. Policymakers are expected to introduce strict measures, carbon-taxing, and carbon-credits for reducing carbon-intensive technologies and industries across the BRICS states. New and existing FDIs, enterprises, production systems, and plants should be comprehensively audited to assess global environmental standards compliance.

Fifth, the presence of positive REC-CO_2e in this study has reinforced the need for expansion in renewable energy use in the current energy combination of the BRICS states. Even though some BRICS states have made progress in cleaning and diversifying their energy mix, the current overdependency on solid and liquid carbon-intensive fuels remains a challenging task. Even though the institutions such as the NDB initially set out with a predominant emphasis on 'green project,' there has been a shift towards railway and infrastructure development projects. Despite these sectors' significance in the less developed BRICS states, the 'green projects' should be kept as a priority goal, especially for power generation projects related to wind, hydro, solar, and biomass.

Finally, this study suffers from but a few limitations. First, this study only tested the current framework using data from the BRICS countries. Perhaps, future studies can validate current findings using other regions and countries. Second, this study adopted CS-ADRL, AMG, and PFMOLS for establishing the short-and long-run associations. Researchers are encouraged to use non-linear models such as the NARDL technique for fresh insight. Third, the present model was built on the EKC framework; however, the STIRPAT model is recommended for new information.

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Figures

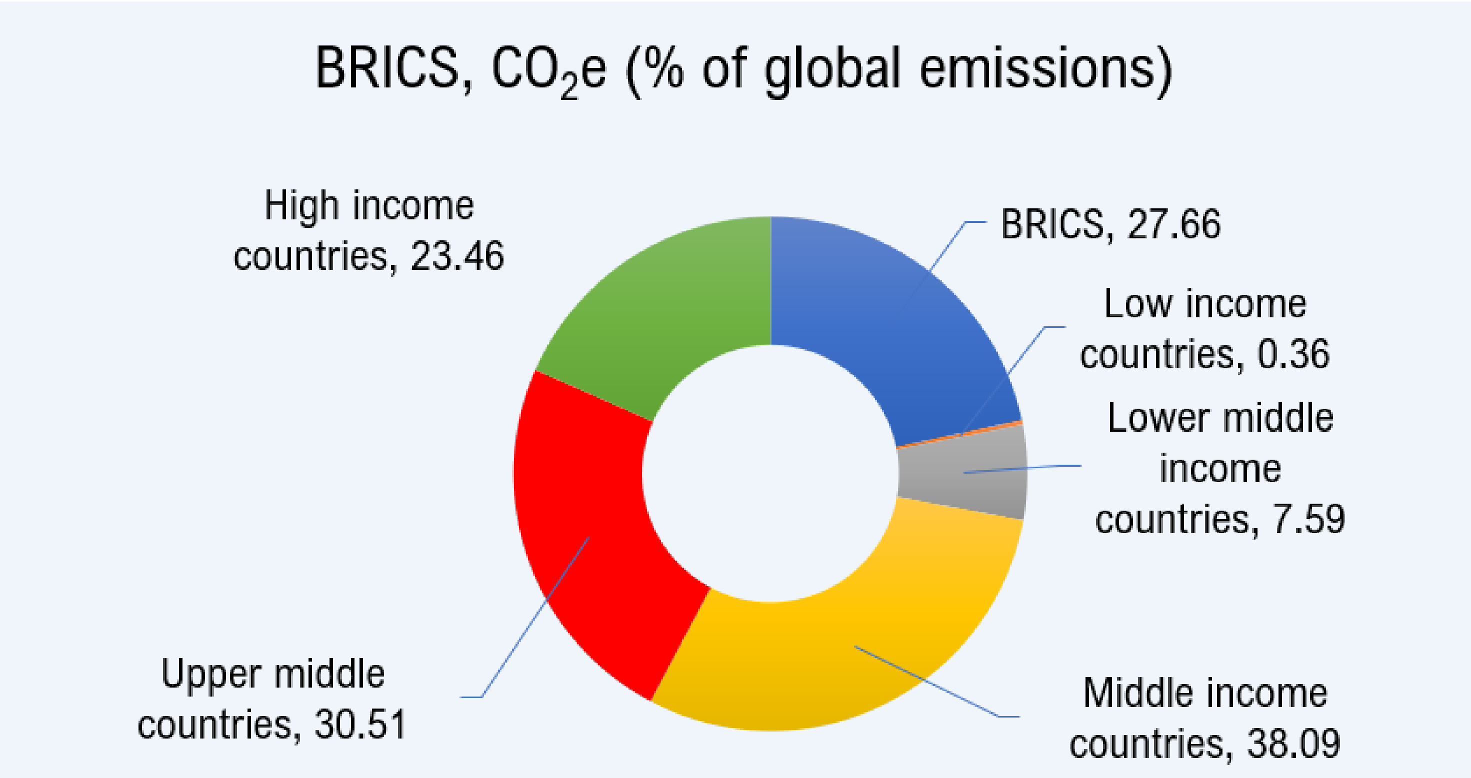

Figure 1

Carbon emissions contribution, BRICS vs. others (% of global emissions).

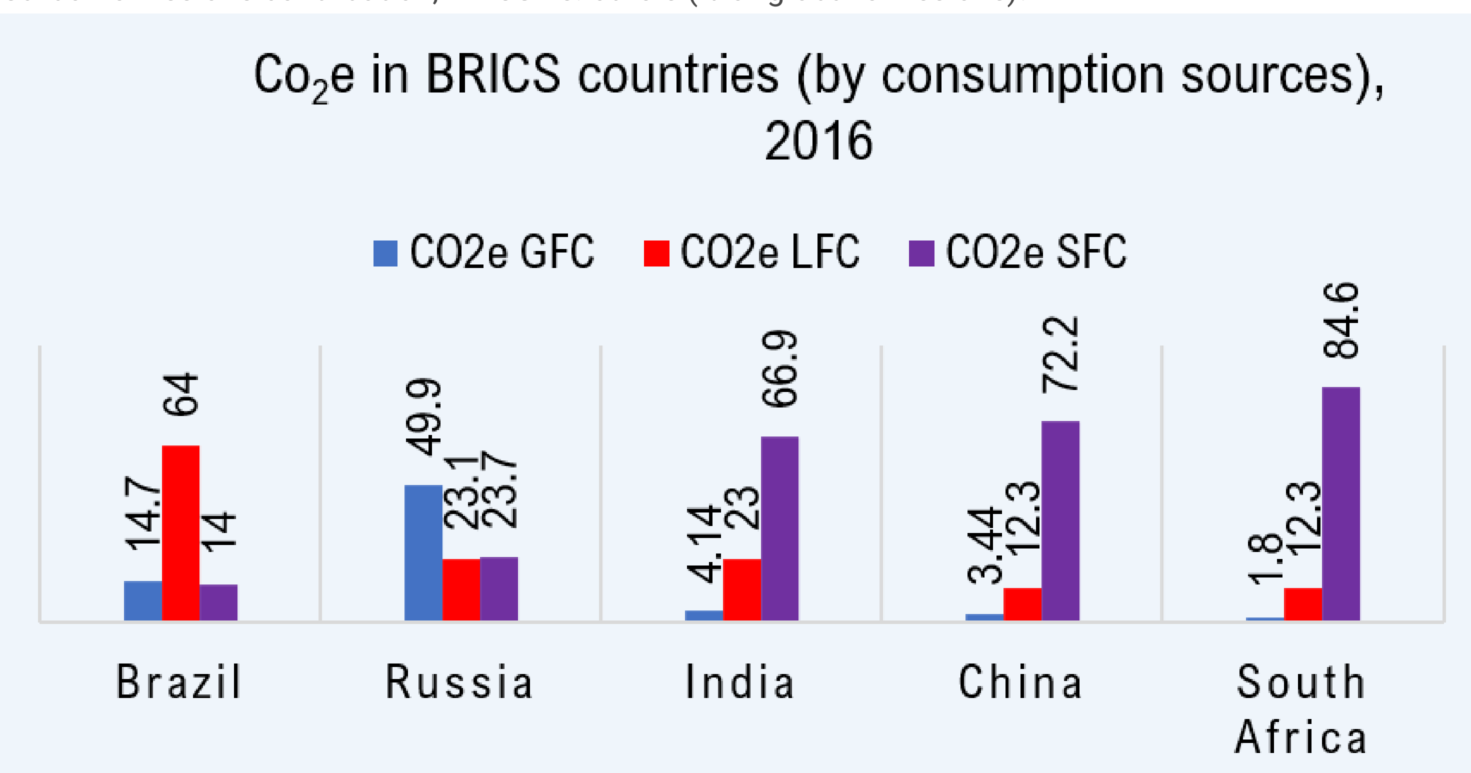

Figure 2

CO2e by different sources in BRICS (%). Abbreviations: SFC= Solid-fuel consumption; LFC = Liquid-fuel consumption; GFC= Gaseous fuel consumption

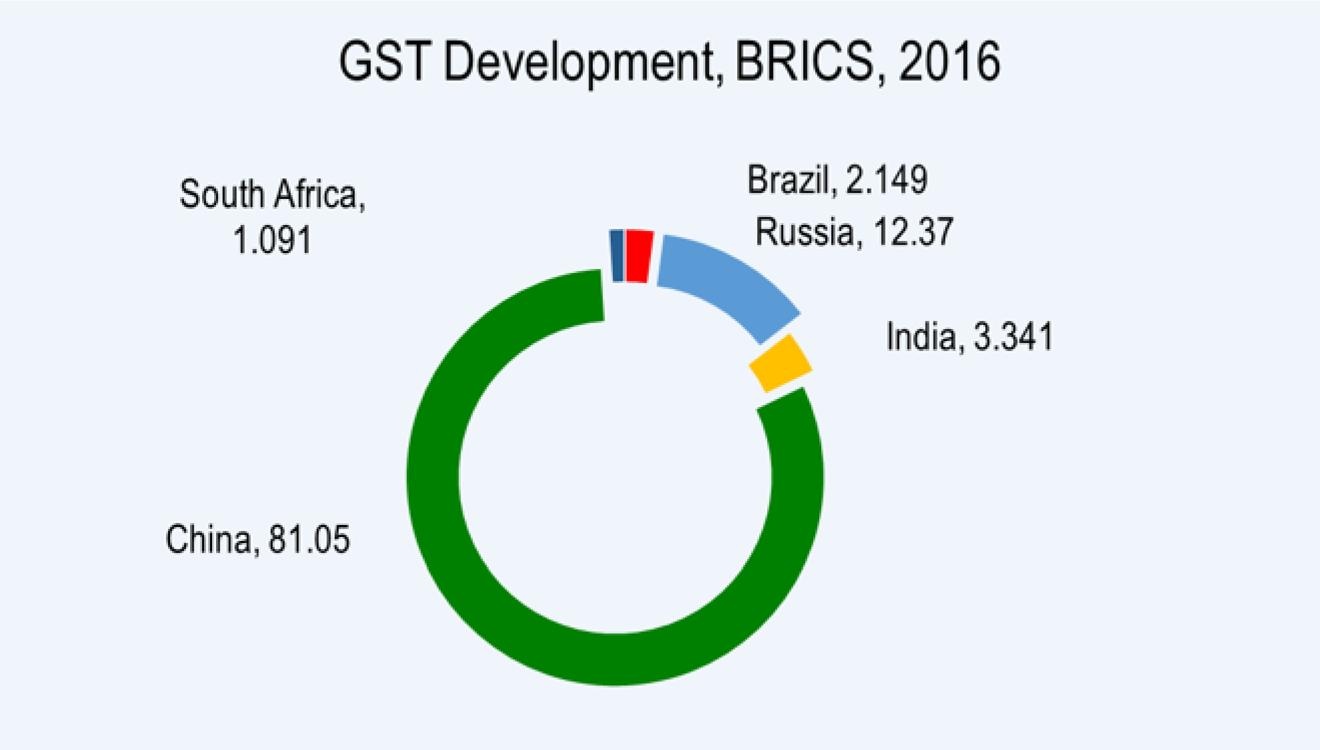

Figure 3

Green and sustainable technology development in BRICS, 2016.

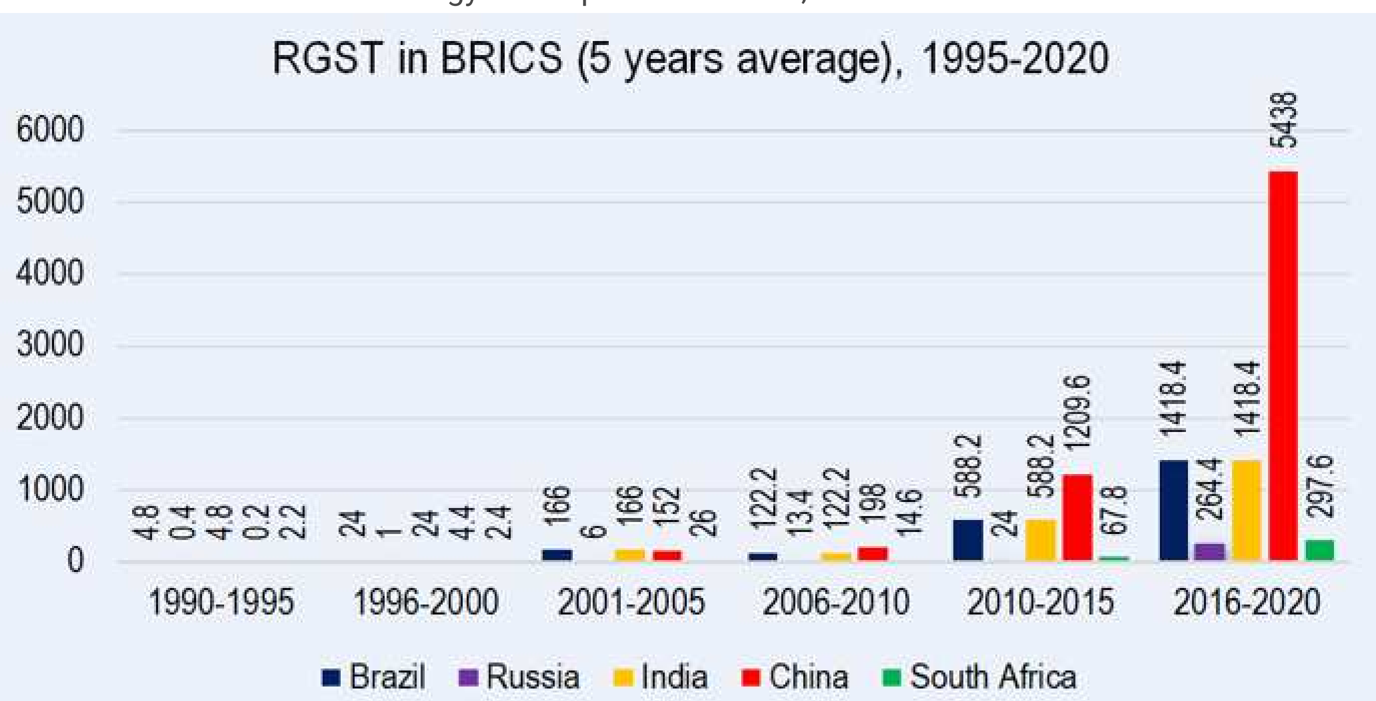

Figure 4

Sector-wise GSTD, BRICS (% of total GST output).

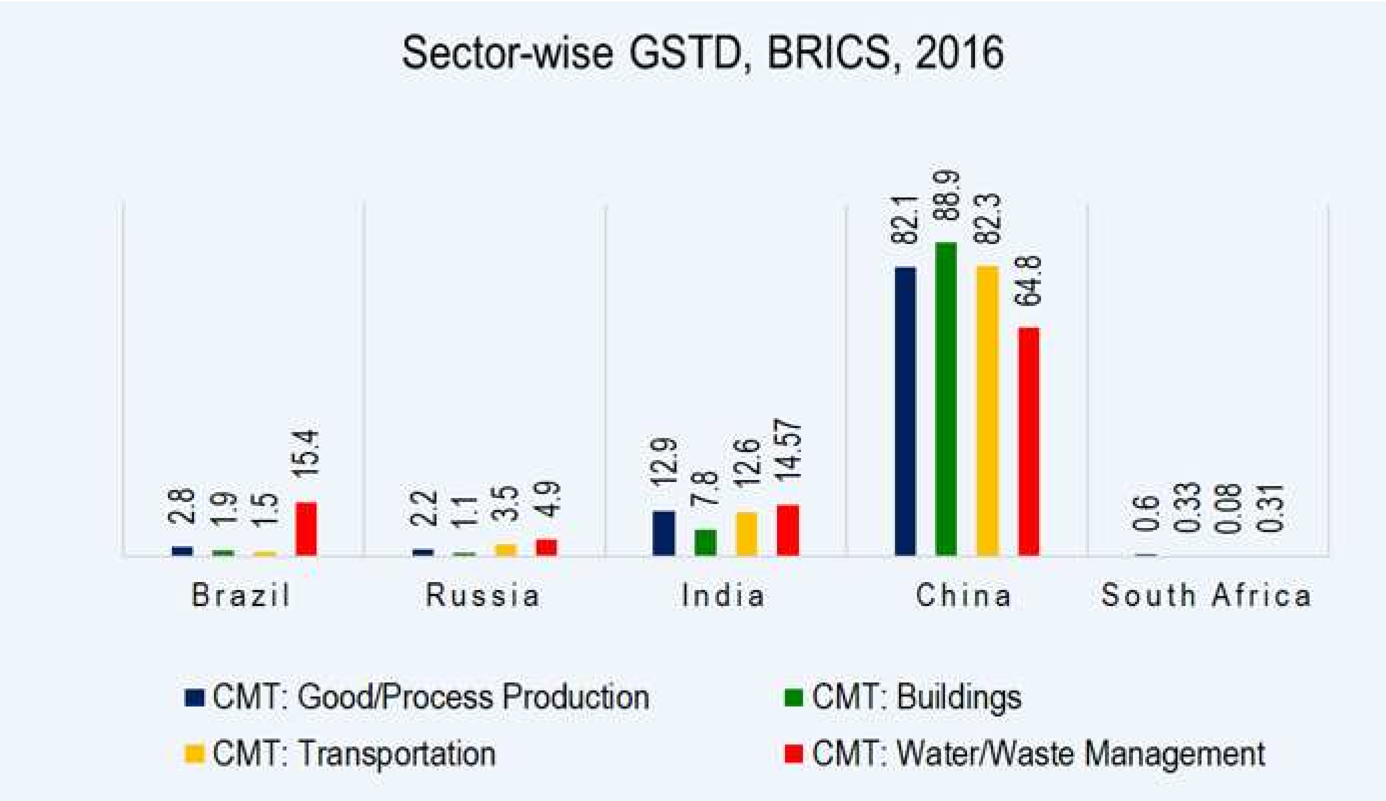

Figure 5

Partnerships in GSTD (by sector), BRICS (% of total GST output), 2016.

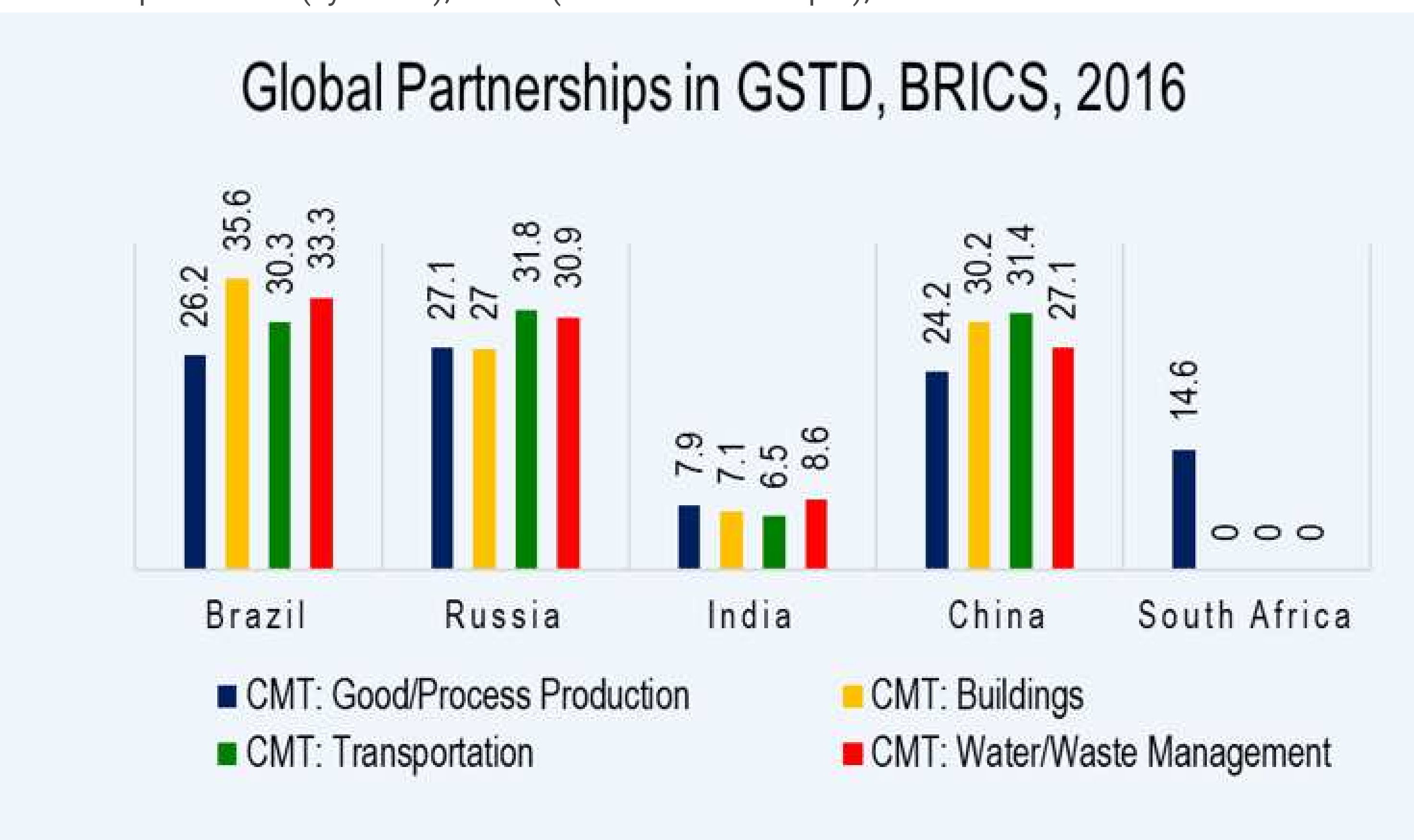

Figure 6

Progress in RGST in BRICS economies from 1990-2020

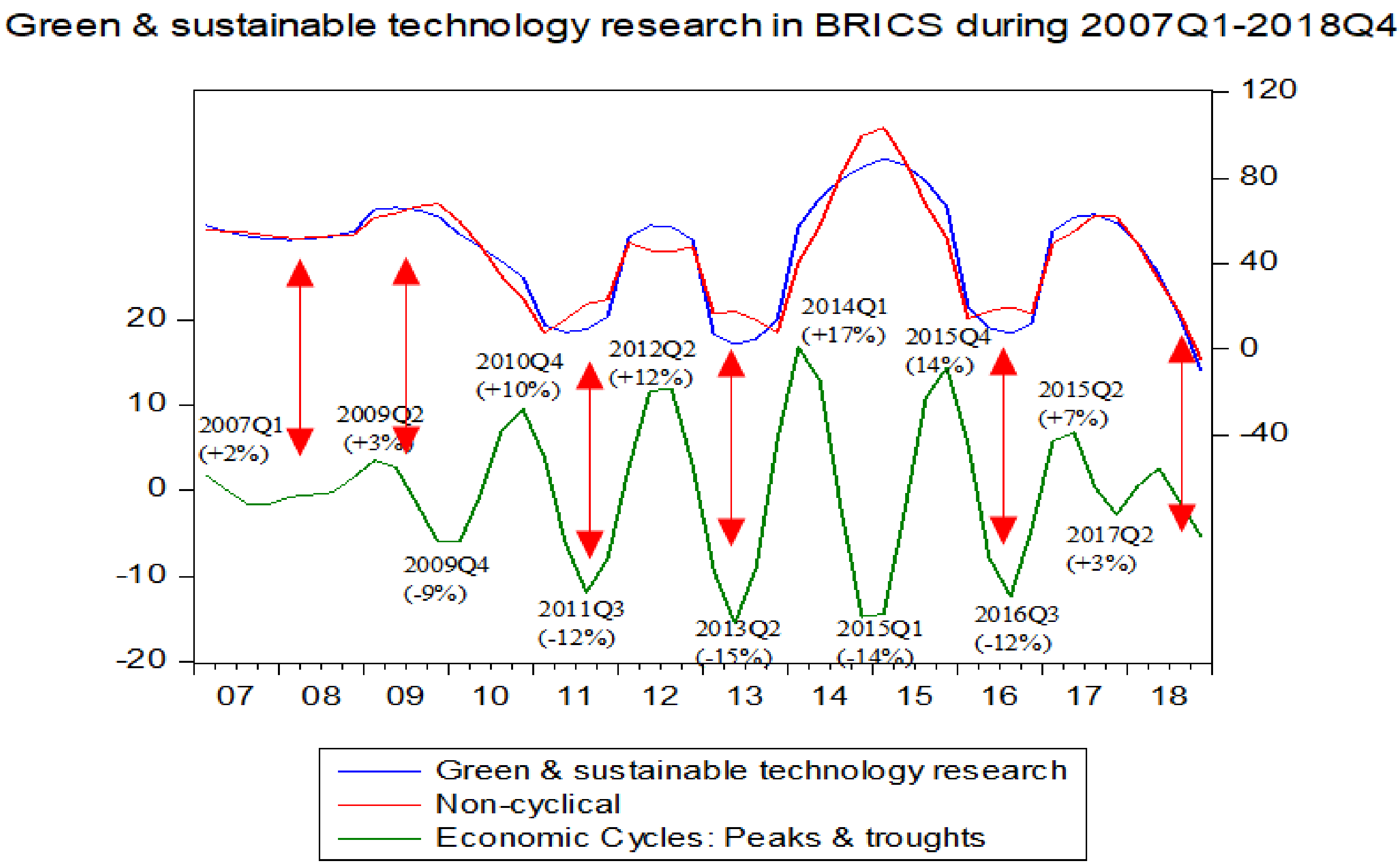

Figure 7

Economic cycles and RGST, BRICS Note. This figure represents a full sample asymmetric (Christiano-Fitzgerald) frequency filter. Cycle periods include low (4.0) and high (8.0). The stationary assumption is assumed to be I(1) random walk.

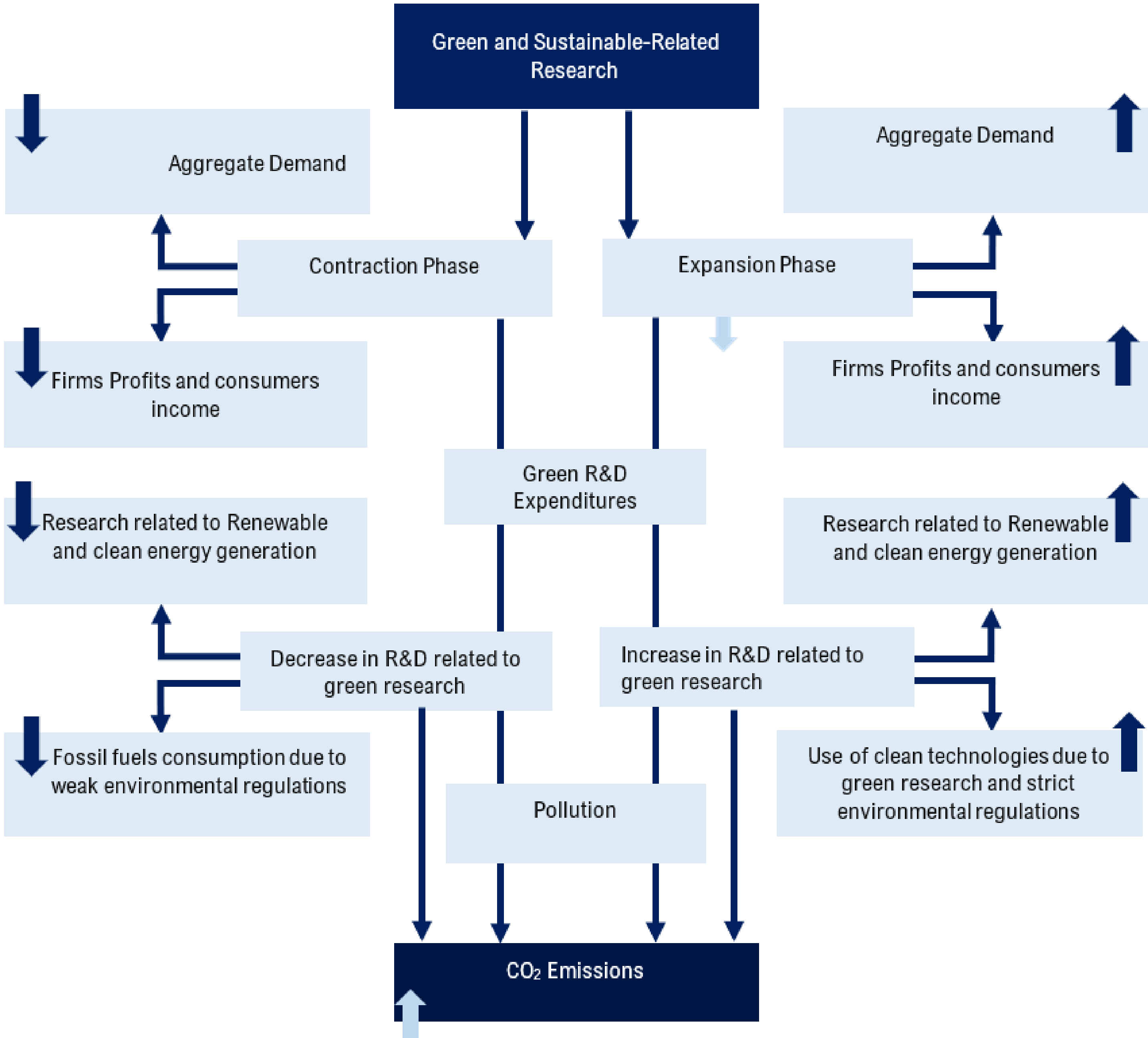

Figure 8

The conceptual framework.