Theoretical Framework for the Carbon Emissions Effects of Technological Progress and Renewable Energy Consumption

Fakhri J. Hasanov¹,²,³ | Zeeshan Khan⁴ | Muzzammil Hussain⁵,⁶ | Muhammad Tufail⁷

¹Energy and Macroeconomics Department, King Abdullah Petroleum Studies and Research Center, Riyadh, Saudi Arabia
²Research Program on Forecasting, Economics Department, The George Washington University, Washington, District of Columbia
³Modeling Socio-economic Processes, Institute of Control Systems, Baku, Azerbaijan
⁴School of Economics and Management (SEM), Tsinghua University, Beijing, China
⁵Business School, University of International Business and Economics, Beijing, China
⁶Faculty of Management Sciences, University of Gujrat, Gujrat, Pakistan
⁷School of Economics and Finance, Xi’an Jiaotong University, Xi’an, China

Correspondence
Muzzammil Hussain, Business School, University of International Business and Economics, Beijing, China.
Email: muzzammil.hussain@uog.edu.pk

Abstract
This study develops a theoretical framework to quantify the impacts of technological progress, renewable energy consumption and international trade on carbon emissions (CO₂), unlike many other studies that consider variables of interest in an ad hoc manner. The developed framework is then applied to the data from the BRICS countries for 1990–2017 period. The study also takes into consideration the integration, co-integration, as well as cross-country interdependence and heterogeneity properties of the panel data, and hence, the obtained results are robust and policy insights are well-grounded. We estimate that technological progress, renewable energy consumption, and export size contribute to the reduction of the CO₂ emissions, while gross domestic product (GDP) and import size increase the pollution both in the long- and short-run. Our main policy recommendations would be the implementations of the measures, regulations, and establishment of the legislative frameworks that foster the technological enhancements and transition toward sustainable energy.

KEYWORDS
international trade, renewable energy consumption, technological innovation, Consumption-based CO₂

1 | INTRODUCTION

Environmental pollution is one of the very urgent issues of humanity. Although there are several types of pollution, air pollution is the central one causing global warming. The core of air pollution is the greenhouse gas emission, and it is mainly driven by carbon dioxide (CO₂). Since CO₂ is considered as the greatest threat to the ecosystem, at the global level, nations set up commitments (e.g., in Kyoto protocol and Paris agreement) and goals (e.g., UN sustainable development goals for 2030) to reduce it. Also, several studies have investigated CO₂ to understand the driving forces behind it. The majority of these studies have considered income and population using either so-called Environmental Kuznets Curve or STIRPAT frameworks and concluded that they are the main reasons for CO₂ emissions. Given that the ultimate purpose of any research is to inform policymaking about the implementation of appropriate measures, these studies were not entirely effective. Simply because, it would not be a useful policy recommendation to suggest that GDP and/or population cause CO₂ emission, and therefore, they should be reduced to mitigate the emission. In this regard, one of the key challenges for the implementation of the measures and policies based on these studies is how to implement them and reduce CO₂ emission without deteriorating the quality of life across nations. There are also many studies in CO₂ literature that have considered other social-economic, demographic, energy indicators alongside GDP and population in their research. However, it is fairly difficult to argue that all of these studies considered the other indicators for the sake of being useful for policymaking to reduce CO₂ emission.
Additionally, many of these studies have considered a set of indicators without providing a theoretical foundation for such considerations. These two points are among the reasons that motivated us in conducting this research here.

To contribute to this discourse, we consider renewable energy consumption and technological innovation in our CO2 analysis. They have three main advantages: they both theoretically are expected to reduce the CO2 emission; they also can support the well-being of the nations. The major sources of renewable energy are solar, hydropower, and solar energy (Zeng, Liu, Liu, & Nan, 2017). Additionally, the expansion of renewable energy consumption, that is, energy transition (ET) toward renewables is one of the key items on the agendas of nations across the world. International Renewable Energy Agency (IRENA) defines ET as a pathway toward the transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century. One of the unique features of ET, which makes it more important for nations is that it can improve three key areas, namely pollution reduction, energy security, and sustainable economic growth. Among them, pollution reduction draws a lot of attention due to the urgency of the issue for the globe. For instance, the International Energy Agency (IEA) puts the environment in the heart of ET. Also, respected energy organizations such as IEA and IRENA consider technological innovations as one of the key drivers for mitigating environmental pollutants (Boshell, 2018). Lastly, recognized institutions including IEA, UN Industrial Development Organization, IRENA, and UN environmental programs affirm that technological innovations can play a considerable role in achieving other SDGs such as poverty reduction, economic growth, food, water and energy security, and health, alongside environmental protection (IEA G20, 2019). Moreover, it is common sense that technological innovations are important for the development of the social-economic and energy systems and pollution mitigation of the nations (Negro & Hekkert, 2008; Suurs & Hekkert, 2009). Innovations, which is the core of technological progress, is considered as the key indicator in the Sustainable Development Goal (SDG) by the United Nations.

The objective of this study is to investigate the consumption-based CO2 effects of technological progress and renewable energy consumption alongside income and international trade. To the best of our knowledge, this is the first study that develops such a framework rather than including the mentioned factors in analyses in an ad hoc manner such as done by many studies in the literature. Second, there are limited studies for the BRICS countries that investigate the role of technological progress and renewable energy consumption in the reduction of the consumption-based CO2.

Third, with an expansion of international trade especially from the BRICS countries’ standpoint, it is imperative to analyze the effect of international trade on CO2. In doing so, earlier studies and those for the BRICS economies considered trade openness in their analyses. However, openness does not allow us to pinpoint the separate impacts of exports and imports on CO2 as it is a composite indicator. Hence, following Hasanov, Liddle, and Mikayilov (2018) and Liddle (2018a), we consider exports and imports as separate variables in the analysis to reveal their individual effects. Fourth, the expansion in international trade, as one of the main streamlines of globalization, makes itself important to be accounted for environmental pollution. Therefore, it is important to consider the consumption-based carbon emission, which is the international trade-adjusted pollution measure. However, literature has focused mainly only on the territory-based CO2 emissions. Recent studies argue that it is better to consider consumption-based CO2 than using territorial-based CO2 (see, for example, Hasanov et al., 2018; Liddle, 2018a). Fifth, this study, unlike many studies in the literature, addresses integration-cointegration as well as cross-country interdependence and heterogeneity features of the panel data. Moreover, cutting edge econometric method, such as Pesaran (2015) cross-sectional test, Pesaran and Yamagata (2008) cross-section slope heterogeneity test, Bai and Carrion-i-Silvestre (2009) unit root test, Westerlund and Edgerton’s (2008) cointegration test, cross-sectional augmented Autoregressive Distributed Lags (CS-ARDL) methods, are employed.

The rest of the sections of this paper are given as Section 2 surveys the existing studies for the BRICS economies along with the
studies that used the consumption-based CO₂ emissions. Section 3 develops a theoretical framework to ground empirical analysis. Section 4 presents the data, and the panel econometric methods. The empirical findings of the study and their discussion are documented in Section 5. Section 6 concludes the research with some policy insights.

2 REVIEW OF LITERATURE

In this section, we focus on two kinds of studies: papers investigated the carbon emissions in BRICS countries and papers considered the consumption-based carbon emissions as the dependent variable. Regarding the first strand of studies, the following studies are worth surveying.

In a study by Azevedo, Sartori, and Campos (2018), the quantitative analysis of carbon emissions and GDP is conducted for the period 1990–2011. The study showed many limitations that including the use of traditional OLS methods for the analysis and mere GDP and lag of CO₂ emissions to check the territory-based carbon emissions. In another study on BRICS by Zakarya, Mostefa, Abbes, and Seghir (2015), the effect of FDI, energy consumption, and economic growth is tested by using co-integration and causality analysis. Findings reported the co-integration and one-way causality from CO₂ emissions to FDI, GDP, and energy consumption. After careful inspection of this study, it can be inferred that the study showed deficiency in terms of model justification, as no theoretical background is given for model construction. After controlling EC & GDP, mere FDI is not enough to determine CO₂ emissions without theoretical support. Moreover, traditional territory-based CO₂ measure is used which do not take into consideration the international trade effect and thereby may bring ambiguous results. Additionally, an analysis of BRICS showed that renewable energy consumption, trade openness, and CO₂ emissions have a long-run equilibrium relationship with feedback hypothesis confirmation by bidirectional causality analysis. However, with the use of traditional territory-based CO₂ emissions, it is not easy to see the true picture of actual CO₂ emissions; moreover, analysis of exports and imports did not take into account separately (Sebri & Ben-Salha, 2014).

Wang et al. (2018) explored the moderating role of corruption in the relationship of economic growth, trade, urbanization, and CO₂ emissions from 1996 to 2015 by using partial least square (PLS) with fixed and random effects. They found the significant moderating role of corruption in determining the CO₂ emissions in BRICS. However, this study also can be enhanced if the trade-adjusted CO₂ measure, as well as the individual effect of exports and imports, were considered. Additionally, the study does not provide any theoretical framework for considering corruption as a determinant of CO₂ emissions. Michieka et al. (2013) investigated exports as a determinant of carbon emissions for China throughout 1970–2010. The results obtained depicted that exports established a unidirectional causal relationship with carbon emissions. The causality found is mainly from exports to carbon emissions. Santra (2017) analyzed the effect of technological innovation on both production-based energy and CO₂ emissions productivity in the case of BRICS countries from 2005 to 2012 by applying the least square dummy variable regression (LSDV) method, Pooleed OLS and fixed-effect method. The study found that environment-related technological innovation has a positive effect on both production-based CO₂ emissions and production-based energy productivity. In a recent study by Adedoyin, Gumede, Bekun, Etokakpan, and Balsalobre-lorente (2020), the role of coal rents is observed in BRICS economies, finding reported the supportive role of coal rents in reducing CO₂ emissions, this study suggests examining the role of technological innovation for sustainable development.

Furthermore, in a recent study of 11 cities of Hubei province of China by Mi et al. (2019), the consumption-based CO₂ emissions are analyzed, and findings disclose that the six modern cities are import-dependent consumers of carbon emissions and remaining five are the opposite. This study used cross-sectional data for the year 2012 only, which may be inadequate to generalize these findings for other provinces and countries. So, a more detailed study is needed to overcome such limitations. Additionally, Wen and Wang (2020), analyzed provincial data of China to calculate carbon leakage by considering production- and consumption-based CO₂ emissions and found the carbon leakage for the provinces. However, this study was also limited to compute only the carbon leakage and did not provide the desired outcome. The common missing point for the BRICS studies above is that their CO₂ measures do not account for the international trade as they used the territory-based CO₂. Also, they did not consider the role of technological innovation in their analyses.

The second strand of literature is based on the studies, which used the consumption-based CO₂ emissions. The most updated empirical study on this area of research is recently conducted by Liddle (2018a); Hasanov et al. (2018), Franzen and Mader (2018), Knight and Schor (2014). However, the study of Peters et al. (2011) and Steinberger et al. (2012) is more of a descriptive kind study and does not associate variables. Liddle (2018a) investigated the nexus between consumption-based carbon emissions and international trade for a panel of 117 countries from 1990 to 2013. For the consumption-based carbon emissions, it was found that exports negatively and imports positively affect consumption-based carbon emissions. Moreover, a positive effect of GDP with consumption-based carbon emissions is also established. Moreover, for consumption-based carbon emissions, both gasoline and domestic oil prices are found insignificant. Similarly, Hasanov et al. (2018) following the same approach studied the impacts of exports and imports on consumption-based carbon emissions for nine oil-exporting countries during 1995–2013. The author established a positive effect of imports and gross domestic product on consumption-based carbon emissions, while, exports are linked negatively with the consumption-based CO₂. However, Franzen and Mader (2018) analyzed 110 OECD and non-OECD countries during 1997–2011, they compare consumption and production-based CO₂ emission and found no carbon leakage. But, they did not examine specifically the consumption-based CO₂ emissions, and the study was focused only on the basic comparison.

Recently, Khan, Ali, Umar, Kirikkaleli, and Jiao (2020) investigated the consumption-based carbon emissions in G-7 countries. Renewable
energy and exports are found helpful to reduce the environmental degradation. Similarly, some relevant studies have contributed to the growth-environment nexus in the recent years in different parts of the world. For example, Alola and Kirikkaleli (2019) in US, Khan, Ali, Jinyu, Shahbaz, and Siquin (2020) explored the consumption-based emissions in nine oil-exporting countries. Moreover, Adebayo, Awosusi, and Adeshola (2020) has re-examined the determinants of carbon emissions in MINT economies. However, they did not consider the most emerging panel of BRICS.

Furthermore, some recent studies have considered renewable energy and innovation to mitigate climactic affects (Ali, Dogan, Chen, & Khan, 2020; Ding, Khattak, & Ahmad, 2021; Dong, Dong, & Jiang, 2020; Dong, Hochman, & Timilsina, 2020; Hussain, Mir, Usman, Ye, & Mansoor, 2020; Su, Naqvi, Shao, Li, & Jiao, 2020). However, the theoretical framework and the nexus hypothesis in this study have not examined before. Moreover, the literature is offering a substantial gap that needs to be filled in order to provide a new insight into the environment-related knowledge.

Therefore, after analyzing all the above-mentioned studies in the first and second strands of the literature, it can be concluded that, although existing literature on BRICS economies has evidence of environment-growth nexus with other macroeconomic variables, the studies are scarce in examining the consumption-based CO₂ emissions. Particularly, the role of technological progress and renewable energy consumption in the consumption-based CO₂ is missing in the literature of BRICS countries. So, it can be proposed that the role of technological innovation and renewable energy consumption might bring innovative outcomes for the BRICS countries, and it may help in the policymaking of these economies. So the present study is an effort to contribute to the existing literature by recruiting technological innovation and renewable energy consumption alongside international trade and income measures.

3 | THEORETICAL FRAMEWORK

This section describes the theoretical foundation of the framework that relates the consumption-based CO₂ to renewable energy consumption and technological innovation alongside income and trade variables. The expanding international trade, as one of the main streamlines of the globalization, makes itself important to be accounted for environmental pollution. Therefore, we considered the consumption-based carbon emission in this study.

There is a Cobb–Douglas production function that links output (Q) to the production factors of labor (L), capital (K), and energy (E) through the technology (A) as given below:

\[ Q = AL^\alpha K^\beta E^\gamma \]  

where, \( \alpha, \beta, \) and \( \gamma \) are the elasticities of \( Q \) concerning \( L, K, \) and \( E, \) respectively. A usually is called total factor productivity (TFP).

The natural logarithmic (ln) transformation of Equation (1) can be expressed as follows:

\[ \ln Q = \ln A + \ln L + \gamma \ln K + \gamma \ln E \]  

It is quite reasonable to consider/assume that TFP is not constant over time (e.g., see Solow, 1957). This is because of the technological developments, innovation, and know-how related activities mainly stemmed from openness, globalization, international competitiveness, catch-up efforts, and convergences among the economies over the world.

Following a standard set of assumptions as it was done by Nordhaus (1975) and Beenstock and Dalziel (1986) among many others, it can be assumed that (i) a cost function exists as a dual function of the production function; (ii) factor pricing is based on average cost and fixed markup; (iii) there is also a preference function in the economy and thus, the demand for goods and services is a function of price and income; (iv) all the functions follow the Cobb–Douglas type of specification; and (v) first-order conditions are derived assuming cost minimization. We can derive the below-expressed the energy demand equation based on (i)-(v) assumptions:

\[ \ln E = \varphi_0 + \varphi_1 \ln Y + \varphi_2 \ln TFP + \varphi_3 \ln \tau Y \]  

where, \( \varphi_0, \varphi_1, \varphi_2, \) and \( \varphi_3 \) are the prices of \( K, L, E; Y \) is income.

For brevity, we do not describe details of the derivation of Equation (3) here as it is not our aim in this research. Step-by-step derivation of an energy demand function such as Equation (3) is described in Mikayilov and Hasanov (2019), and interested readers can refer to that paper. Hasanov et al. (2019) empirically estimate energy as a function of TFP alongside other determinants such as price and income.

As Hasanov and Mikayilov (2020) discuss, following Nordhaus (1975) and Beenstock and Dalziel (1986) among others, Equation (3) can be reduced to Equation (4), where prices of other inputs than energy are dropped based on some assumptions discussed below.

\[ \ln E = \varphi_0 + \varphi_1 \ln Y - \varphi_2 \ln TFP - \varphi_3 \ln \tau_1 \]  

For example, seminal studies such as Nordhaus (1975) and Beenstock and Dalziel (1986) assume that the price of capital is linearly dependent on GDP deflator and price of labor is proportional to income, and they end up with a reduced form of the equation, in which price of other production factors are dropped. Other studies in the energy demand literature also excluded the price of other production factors from the energy demand equation by assuming long-run homogeneity among those prices and the price of energy (see e.g., Shirani-Fakhr, 2015).

Considering that energy is the sum of fossil fuels energy (EF) and renewable energy (ER), then equation (4) can be written as:
\[ \ln(\text{EF} + \text{ER}) = \varphi_0 + \varphi_1 \ln Y - \varphi_2 \ln \text{TFP} - \varphi_3 \ln p_e \]  
(5)

If we apply Taylor expansion to the left-hand side of equation (5) and ignore the high-order terms and constant term, the following expression will be obtained:

\[ \ln(\text{EF} + \text{ER}) \approx \text{EF} + \text{ER} \]

Now, equation (5) can be written as below:

\[ \text{EF} = \varphi_0 + \varphi_1 \ln Y - \varphi_2 \ln \text{TFP} - \varphi_3 \ln p_e - \text{ER} \]  
(6)

CO\text{2} is produced in a given territory when fossil fuels are burned, and there are conversion scalars called emission factors for each fuel type (e.g., see https://www.eia.gov/tools/faqs/faq.php?id=73&t=11). Based on this relationship, it can be expressed that total territory-based CO\text{2} emissions is proportional to total fossil fuels energy: \( \text{CO2T} = k \cdot \text{EF} \)

Using this relationship, equation (6) can be re-expressed as follows:

\[ \text{CO2T} = (l_0 + l_1 \ln Y - l_2 \ln \text{TFP} - l_3 \ln p_e - l_4 \text{ER}) \]  
(7)

where, \( l_0 = \varphi_0 \), \( l_1 = \varphi_1 \), \( l_2 = \varphi_2 \), \( l_3 = \varphi_3 \), \( l_4 = \frac{1}{k} \).

Equation (8) below expresses the relationship between territory-based CO\text{2} and consumption-based CO\text{2}:

\[ \text{CO2C} = \text{CO2T} - \text{CO2X} + \text{CO2M} \]  
(8)

The equation just simply states that consumption-based CO\text{2} can be calculated by subtracting CO\text{2} embedded in exports (CO\text{2X}) from territory-based CO\text{2} and adding CO\text{2} embedded in imports (CO\text{2M}).

Following Liddle (2018b), we can make the following re-expression:

\[ \text{CO2C} = \text{CO2T} - \text{CO2X} + \text{CO2M} = \text{CO2T} \left(1 - \frac{\text{CO2X}}{\text{CO2T}} + \frac{\text{CO2M}}{\text{CO2T}} \right) \]  
(9)

where, \( \frac{\text{CO2M}}{\text{CO2T}} = \frac{M}{Y} + \frac{Y}{M} \), \( M \) and \( Y \) are imports and GDP, respectively. The same identity is true for \( \frac{\text{CO2X}}{\text{CO2T}} \). That is, \( \frac{\text{CO2X}}{\text{CO2T}} = \frac{X}{Y} + \frac{Y}{X} \) and \( \frac{\text{CO2M}}{\text{CO2T}} = \frac{M}{Y} + \frac{Y}{M} \).

Accounting the above identities in equation (9) yields the following relationship:

\[ \text{CO2C} = \text{CO2T} \left(1 - \frac{\text{CO2X}}{\text{CO2T}} + \frac{\text{CO2M}}{\text{CO2T}} \right) = \text{CO2T} \left(1 - \frac{X}{Y} \cdot \frac{\text{CO2X}}{\text{CO2T}} + \frac{M}{Y} \cdot \frac{\text{CO2M}}{\text{CO2T}} \right) \]  
(10)

Since BRICS counties do not price/tax carbon in their exports and imports (He et al., 2020) to the best of our knowledge, \( \frac{\text{CO2X}}{\text{CO2T}} = 1 \) and \( \frac{\text{CO2M}}{\text{CO2T}} = 1 \) can be written. Then, equation (10) can be expressed as:

\[ \text{CO2C} = \text{CO2T} \left(1 - \frac{X}{Y} + \frac{M}{Y} \right) \]  
(11)

Equation (11) can be written for territory-based CO\text{2} as follows:

\[ \text{CO2T} = \frac{\text{CO2C}}{\left(1 - \frac{X}{Y} + \frac{M}{Y} \right)} \]  
(12)

Substituting CO\text{2T} in equation (7) with its expression in equation (12) and writing the resulting expression for CO\text{2C} would yield the following equation:

\[ \text{CO2C} = \left(1 - \frac{X}{Y} + \frac{M}{Y}\right) \ln(\text{EF} + \text{ER}) + \ln(l_0 + l_1 \ln Y - l_2 \ln \text{TFP} - l_3 \ln p_e - l_4 \text{ER}) \]  
(13)

Taking the natural logarithmic expression of equation (13) yields equation (14) as written below:

\[ \ln \text{CO2C} = \ln \left(1 - \frac{X}{Y} + \frac{M}{Y}\right) + \ln(l_0 + l_1 \ln Y - l_2 \ln \text{TFP} - l_3 \ln p_e - l_4 \text{ER}) \]  
(14)

Lastly, applying Taylor expansion to the right-hand side components of equation (14) and ignoring high-order terms, multiplication of the variables and constant terms, which lead to a complicated nonlinear relationship will produce the following relationship:

\[ \ln \text{CO2C} = \frac{M}{Y} + X \cdot \ln Y - \frac{X}{Y} \cdot \ln \text{TFP} - \frac{X}{Y} \ln p_e - \frac{X}{Y} \text{ER} \]  
(15)

For the purposes of empirical analyses, one can homogenize and simplify equation (15) as follows:

In this section, our main purpose is to theoretically derive signs for the explanatory variables impacting carbon emissions. In this regard, equation (15) gives us an idea about the sign of the impacts of the right-hand side variables on the consumption-based CO\text{2}. Regardless of whether we take exports and imports percentage shares in GDP and renewable energy or natural logarithmic transformations of them, their signs do not change because none of these variables will likely take values being smaller than unity. Therefore, as Liddle (2018b) did, we can also take the natural logarithmic transformations of the shares of exports, imports, as well as renewable energy to have a homogenized relationship, that is, log-log specification in (15). The log-log specification is straightforwardly interpretable. Another advantage of the logarithmic transformation of variables is that it can significantly reduce issues such as heteroscedasticity and non-normality in the econometric estimations. Also, if a variable is expressed in the natural logarithm, then its coefficient can be directly interpreted as an elasticity. Log-log version of equation (15) will be as:
\[
\ln \text{CO}_2 = b_1 \ln \left( \frac{M}{Y} + 100 \right) - b_2 \ln \left( \frac{X}{Y} + 100 \right) - b_3 \ln \text{ER} + b_4 \ln Y - b_5 \ln \text{TFP} - b_6 \ln p_e
\]  

(16)

where, \(b_4, b_5, b_6 \) are for simplicity.

It is quite reasonable to expect a high positive correlation between the price of fossil fuels energy, \(p_e\), and renewable energy, ER. This is simply because when the prices of fossil fuels energy carries are high, then people will increase the share of renewables in their energy consumption mix. The opposite is also true: low prices of fossil fuels energy can result in less share of renewables in the energy mix. To this end, one may wish to drop either the price of fossil fuels energy or renewable energy from equation (16). Considering that fossil energy carries can result in less share of renewables in the energy mix, one may drop the price. Thus, equation (16) reduces as written below:

\[
\ln \text{CO}_2 = b_1 \ln \left( \frac{M}{Y} + 100 \right) - b_2 \ln \left( \frac{X}{Y} + 100 \right) - b_3 \ln \text{ER} + b_4 \ln Y - b_5 \ln \text{TFP}
\]  

(17)

To make equation (17) an econometric specification, we add an intercept \((b_0)\) and error term \((e)\) to it. We also denote the logarithmic expressions with small letters, i.e., \(\ln \text{CO}_2 = cco_2\), \(\ln \left( \frac{M}{Y} + 100 \right) = m\), \(\ln \left( \frac{X}{Y} + 100 \right) = x\), \(\ln \text{ER} = er\), \(\ln Y = y\), \(\ln \text{TFP} = tfp\). Thus equation (17) becomes:

\[
cco_2 = b_0 + b_1 m - b_2 x - b_3 er + b_4 y - b_5 tfp + e
\]  

(18)

Theoretically, we expect that consumption-based CO2 will be negatively affected by an export share in GDP, renewable energy, and TFP while GDP and import share in GDP will exert positive impacts.

### TABLE 1  
Nomenclature of variables and sources

| Variable   | Definition                                                                 | Measurement                  | Sources                        |
|------------|---------------------------------------------------------------------------|------------------------------|--------------------------------|
| CCO2it     | It is equal to territory-based consumption subtracting carbon emissions embodied in exports plus carbon emissions embodied in imports. | Million tonnes of CO2, (MtCO2) | Global Carbon Atlas (2019)     |
| Xi_t       | Exports of goods and services were measured at constant 2010 US dollars.   | Percentage of GDP            | World Bank (2019)              |
| Mi_t       | Imports of goods and services were measured at constant 2010 US dollars.   | Percentage of GDP            | World Bank (2019)              |
| Yit        | The final value of all the goods and services that are produced within the boundaries of a country at a specific time. | Measured in Constant 2011 US dollars and adjusted for purchasing power paraty (PPP) | World Bank (2019)              |
| TFPit      | Patents acquired by both residents and nonresidents of each country.       | Total number of patents       | World Bank (2019)              |
| ERi_t      | Consumption of energy obtained from renewable sources, that is, hydro, wave, tidal, wind, geothermal, and solar. | Percentage of the total energy consumption | World Bank (2019)              |
4.1 Cross-section dependence and slope heterogeneity tests

In the modern era, with increasing economic integration, lowering trade barriers, or in the era of globalization, cross-section dependence in the panel data econometrics is most likely to occur. Ignoring the issue of cross-section dependence and assuming independence between cross-section may lead to misleading information, inconsistent, and biased results from the estimators (Grossman & Krueger, 1995; Westerlund, 2007). To test for cross-section dependence, Pesaran (2015) test for weak exogenous cross-section dependence in the large panel data econometrics is used. Similarly, without checking for slope heterogeneous coefficient and assuming homogenous slope coefficient shall provide misleading estimator results (Breitung, 2005; Jalil, 2014). Therefore, cross-section slope heterogeneity is tested using an adjusted version of Swamy’s (1970) developed by Pesaran and Yamagata (2008). Before unit root tests, it is imperative to first check for the presence of cross-section dependence and cross-section slope homogeneity to employ relevant panel data econometric unit root tests.

4.2 Panel unit root tests

In the presence of heterogeneous cross-sectional slopes for coefficients and cross-section dependence, the use of first-generation panel unit root tests, that is, Fisher-augmented Dickey-Fuller (Fisher-ADF), I’m, Pesaran & Shin (IPS), Fisher Phillips-Perron, and Levin-Lin and Chu (LLC) is not valid. Since first-generation panel unit root tests do not allow for cross-section dependence and even LLC does not even allow for a heterogenous cross-sectional slope coefficient. Therefore, this study uses Pesaran (2007) cross-sectionally augmented Dickey-Fuller (CADF), Bai and Carrion-i-Silvestre (2009) panel unit root tests which not only deal only the problem of cross-section dependence, slope heterogeneous coefficient but the later one even captures possible multiple structural breaks in each series. Bai and Carrion-i-Silvestre (2009) also deal with unobserved dynamic factors.

4.3 Panel co-integration tests

The use of first-generation tests, McCoskey and Kao (1998), Westerlund (2005), and Pedroni (2004) in the presence of structural breaks, cross-sectional heterogeneous slope coefficient is invalid. This study uses two-panel cointegration approaches, that is, Westerlund (2007) and Westerlund & Edgerton’s (2008). Westerlund (2007) approach uses four statistics, two for group mean statistics and two for panel statistics. Group means statistics are denoted by Gt and Gx, while Pt and Px for cointegration. Westerlund (2007) cointegration is also robust to slope homogeneity and cross-section dependence. Besides Westerlund (2007), this study also uses Westerlund and Edgerton’s (2008) with the power of dealing with cross-section dependence and is robust to the heterogeneous slope, the serial correlation for the cross-section as well as structural breaks in each cross-section at different locations. This approach is used for the long-run or co-integration relationship among the sampled variables.

4.4 Cross-sectional augmented ARDL

The issue of cross-section dependence is dealt with using a newly proposed approach by Chudik et al. (2017) and Chudik and Pesaran (2015). This approach augments the conventional autoregressive distributed lags model (ARDL) by including cross-sectional averages of regressors and the dependent variable. The baseline regression model for cross-sectionally augmented ARDL (CS-ARDL) is given below as:

\[ y_t = \sum_{i=1}^{N} \delta_i y_{i,t-1} + \sum_{i=1}^{N} \gamma_{i,t} x_{i,t-1} + \sum_{i=1}^{N} \theta_{i} y_{i,t-1} + e_t \]  

(19)

In equation (19), \(X'_{t-1} = \{Y'_{t-1}, Z'_{t-1}\}\) \(Y_t\) and \(Z_t\) are for the averages of cross-sections. The averages of both dependent and independent variables are denoted by \(X_{t-1}\) in Equation (19). The long-run and mean group coefficients are calculated as given below:

\[ \hat{\delta}_{CS-ARDL} = \frac{\sum_{i=1}^{N} \delta_i}{1 - \sum_{i=1}^{N} \epsilon_i} \]  

(20)

\[ \hat{\delta}_{mean group(MG)} = \frac{1}{N} \sum_{i=1}^{N} \delta_i \]  

(21)

where equation (20) provides long-run coefficients and equation (21) is for mean group estimator. This study uses CS-ARDL over cross-section augment distributed lags (CS-DL) due to various reasons. CS-DL is not robust as CS-ARDL, although it is superior to the conventional ARDL. Also, the CS-DL does not allow for feedback effects on regressors from dependent variables, but CS-ARDL does (Chudik et al., 2013). Since CS-ARDL is robust to endogeneity issue, it perfectly fits our case here as we may potentially have endogeneity between the consumption-based CO2 and regressors such as GDP or renewable energy consumption.

5 RESULTS

This section provides the results of the econometric estimations and testing. The first section covers the results of cross-section dependence, slope heterogeneity, and unit root tests, while the second part discusses the cointegration test as well as long- and short-run estimations results. Table 2 shows results obtained from the Pesaran (2015) test for cross-section dependence (Panel A) and the results of the Swamy’s (1970) slope heterogeneity test standardized by Pesaran and Yamagata (2008) (Panel B).

The results for cross-section dependence reject the null hypothesis of no cross-section dependence in units meaning that our variables
TABLE 2  Cross-section dependence and slope heterogeneity tests

| Panel A: Cross-section dependence test by Pesaran (2015) | Variable   | Test statistic |
|--------------------------------------------------------|------------|----------------|
| cco2it                                                 |            | 15.048***      |
| Xit                                                    |            | 16.652***      |
| mit                                                    |            | 16.701***      |
| Yit                                                    |            | 16.430***      |
| tfp                                                    |            | 16.683***      |
| erit                                                   |            | 16.681***      |

Panel B: Slope heterogeneity test

| Delta_tilde                                           | 11.629***  |
| Delta_tilde adjusted                                  | 13.251***  |

*Indicates significance level for 10%.
**Indicates significance level for 5%.
***Indicates significance level for 1%.

TABLE 3  Panel unit root tests results

| Panel A: Pesaran (2007) test results | Variables | Level | Test statistics |
|-------------------------------------|-----------|-------|-----------------|
|                                     |           | CIPS  | M-CIPS          |
| cco2it                              |           | -3.08 | -4.87           |
| Xit                                 |           | -2.76 | -3.95           |
| mit                                 |           | -2.88 | -4.25           |
| Yit                                 |           | -1.224| -2.661          |
| tfp                                 |           | -2.26 | -3.22           |
| erit                                |           | -2.47 | -4.68           |

|                                     | First difference | CIPS  | M-CIPS          |
|-------------------------------------|-------------------|-------|-----------------|
| cco2it                              | -4.79***          | -13.36***|
| Xit                                 | -5.02***          | -13.62***|
| mit                                 | -4.96***          | -13.74***|
| Yit                                 | -4.31**           | -6.804*  |
| tfp                                 | -4.21**           | -8.37**  |
| erit                                | -4.14**           | -9.07**  |

Panel B: Bai and Carrion-i-Silvestre (2009) test results

|                                | Test statistics |
|--------------------------------|-----------------|
|                                | Z               | P               |
|                                | Pm              | Z              | Pm          |
| cco2it                         | -1.026          | 0.68            | 46.08*      | -1.29       | 2.12**       | 59.04***  |
| Xit                            | -0.948          | 0.76            | 46.82*      | -1.96**     | 1.48*        | 53.24**   |
| mit                            | -0.714          | -0.23           | 37.89       | -1.74**     | 2.04**       | 58.29***  |
| Yit                            | 1.331*          | -0.304          | 20.642      | 1.762**     | 2.26**       | 49.89**   |
| tfp                            | -1.142          | 1.11            | 49.93*      | -0.69       | 2.01**       | 58.04***  |
| erit                           | -0.286          | -0.894          | 31.99       | -0.93       | 1.80**       | 56.10***  |

*Indicates significance level for 10%.
**Indicates significance level for 5%.
***Indicates significance level for 1%.

Table 3 tabulates panel unit root results obtained from Pesaran (2007) and Bai and Carrion-i-Silvestre (2009) tests.

The results of the Pesaran (2007) unit root test decisively suggest that the levels of the variables have a unit root while the first differences of the levels are stationary. The results of the Bai and Carrion-i-Silvestre (2009) test support the results from the Pesaran (2007) test although they show level stationarity for few variables. However, the evidence of the level stationarity for these variables is very weak as only one out of three test statistics (i.e., P statistic for cco2it, Xit and tfp, and the Z statistic for Yit) suggest so and only at the 10% significance level. Overall, the results of the tests indicate that all the variables are nonstationary, that is, they are the unit root processes at their level, and the first differences of them are stationary. Table 4 reports the outcomes of the Westerlund and Edgerton (2008) and the Westerlund (2007) tests for panel co-integration.

The sample values of the $Z_{(N)}$ and $Z_{(N)}$ statistics reject the null hypothesis of no co-integration at the 1 and 5% significant levels, respectively, which favor that the variables, that is, cco2it, Xit, mit, Yit, tfp, and erit, are cointegrated. As for the results of the Westerlund (2007) test, one panel and one group mean test statistics, that is, Pt and Gt, suggest co-integration among the variables while the other two cannot reject the null hypothesis of no co-integration. Being unable to reject the null hypothesis is quite common for these test statistics, as it is well known that Westerlund (2007) test leads to under-rejection in small samples. For example, he in Westerlund (2007) discusses that Gt statistic fail to reject the null hypothesis in small samples.

Given that the variables are co-integrated, the following two things should be valid: (a) estimation of the level relationship is not spurious and the estimated coefficients can be used for analysis and forecasting; (b) there should be equilibrium error correction representation of the co-integration relationship among the variables. To this end, we estimate the long-run/level relationship as well as short-run dynamics for our dependent variables using the CS-ARDL method. Table 5 documents the results.

Table 4 Co-integration test results

| Panel A: Westerlund and Edgerton (2008) test results |          |          |
|-----------------------------------------------------|----------|----------|
| Variable                                            | Z(N)     | Z(N)     |
| Sample value                                        | -3.521***| -2.95**  |
| p value                                             | .000     | .011     |

| Panel B: Westerlund (2007) test results             |          |          |
|----------------------------------------------------|----------|----------|
| Sample value                                        | -2.744** | -6.903   | -7.719*  | -7.310   |
| p values                                            | .038     | .999     | .067     | .981     |

*Indicates the rejection of the null hypotheses at the 10% significance level.
**Indicates the rejection of the null hypotheses at the 5% significance level.
***Indicates the rejection of the null hypotheses at the 1% significance level.

are not independent of each other across the sections, that is, countries. The sample values of Swamy’s (1970) test and adjusted version of it both reject the null hypothesis of homogenous suggesting that the slope coefficients for each cross-section are heterogeneous.

Table 3 tabulates panel unit root results obtained from Pesaran (2007) and Bai and Carrion-i-Silvestre (2009) tests.

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Apparently, from the table, both the long- and short-run estimation results are reasonable, as the signs of the obtained coefficients are consistent with the theoretical expectations as discussed in Section 3. Moreover, the estimated coefficients of the explanatory variables are statistically significant at the conventional levels.
Discussion

According to Table 2, GDP in China is correlated with that in other countries in our sample. Such kind of interdependences among the variables across Brazil, China, South Africa, Russia, and India are expected due to some reasons including but not limited to globalization, regional connectivity, and spillover effect through international relations including trade, local, and global economic shocks that are common for all of them (see discussions in Liddle and Hasanov, 2020; Pesaran, 2015).

Nonstationarity of having unit root implies that the variables drifting over time, and hence, they do not return to their previous mean as the mean changes over time. Any shock to such kind of drifting series can create a permanent effect. It would be difficult to predict future values of the (log) levels of the variables due to the changing mean and permanent effects of shocks. One should use the stationary transformation of the variables for prediction purposes as mean, variance, and covariance of the stationary series do not change over time, and they “dance” around their mean values. In other words, the stationary series revert to their mean, and hence, they are called mean-reverting process.

Consumption-based CO2 establishes a long-run relationship with export shares in GDP, imports share in GDP, renewable energy consumption, GDP, and TFP. Put differently, consumption-based CO2 shares a common trend with these variables, and they move together and establish an equilibrium relationship in the long-run. Another interpretation of the co-integration is that the relationship between the (log) levels of the variables is not spurious, they are consistent with economic or environmental theory and thereby one can use the long-run coefficients to make analysis and projections. To this end, we estimated the long-run impacts of the mentioned variables on consumption-based CO2 and reported the results Panel A of Table 5.

According to the results, in ceteris paribus, a 1% increase in the export share in GDP results in a 0.22% decrease in the consumption-based CO2 in the long-run. Theoretically, as we discussed in Section 3, the more export from a country, the fewer goods and services are consumed domestically. These countries export a considerable amount of goods and services to other countries. For example, China is leading country in the world in terms of exports, which accounts for 2.41 trillion US dollars (USD) as per 2017 estimations, followed by Russia with 341 billion USD, India 292 billion USD, Brazil 219 billion USD, and South Africa 108 billion USD (Simoes et al., 2011). Our exports related finding here are consistent with (Hasanov et al., 2018). Opposite to the finding for the exports, a 1% increase in the import share in GDP causes a 0.23% rise in consumption-based CO2 in the long-run keeping all other factors constant. As developing economies, BRICS countries import a significant amount of intermediate as well as final goods and services. Higher imports mean more domestic consumption and thereby more consumption-based CO2. Imports contribute to the national consumption level considerably. For example, China imports 1.54 trillion USD, Brazil 140 billion USD, India 417 billion USD, Russia 221 billion USD, and South Africa 81.9 billion USD from the rest of the world (Simoes et al. 2011).

The long-run estimation results show that, in ceteris paribus, a 1% increase in GDP leads to a 0.42% rise in the consumption-based CO2. This finding is in line with the theoretical framework of Section 3. Additionally, the environmental theories such as the STIRPAT and the EKC predict that GDP can result in more CO2 emissions: a rise in the economic activity or income level is associated with more consumption of intermediate and final goods and services, which will bring more CO2 emissions.

Panel A further document that a 1% expansion in renewable energy consumption reduces the consumption-based CO2 by 0.66% holding other factors unchanged in the long-run. As we discussed in Section 3, considering total energy consumption as a sum of the consumption of fossil fuels and renewable energy sources, an increase in the latter source will reduce the share of the former source, and hence CO2 emissions will be reduced. According to the International Renewable Energy Agency, the BRICS countries are avoiding a considerable amount of carbon emissions with the increasing level of investment in}

### Table 5: Long-run and short-run results from the CS-ARDL

#### Panel A. long-run results

| Regressors | Coefficient | SE | z   | p > z |
|------------|-------------|----|-----|-------|
| ER         | -0.218*     | 0.126 | -1.730 | .083  |
| Mx         | 0.225***    | 0.064 | 3.520 | .000  |
| Ye         | 0.415*      | 0.231 | 1.790 | .073  |
| ER         | -0.658***   | 0.093 | -7.050 | .000  |
| TFP        | -0.087***   | 0.028 | -3.130 | .002  |

#### Panel B. short-run results

| Regressors | Coefficient | SE | z   | p > z |
|------------|-------------|----|-----|-------|
| ECT −1     | -0.914***   | 0.103 | -8.890 | .000  |
| Δco2       | 0.086       | 0.103 | 0.830 | .405  |
| Δx         | -0.170*     | 0.106 | -1.610 | .107  |
| Δm         | 0.186***    | 0.044 | 4.260 | .000  |
| Δy         | 0.446*      | 0.247 | 1.800 | .071  |
| Δet        | -0.567***   | 0.049 | -11.650 | .000  |
| Δtfp       | -0.080***   | 0.030 | -2.660 | .008  |

Note: Dependent variable is co2it. The Intercept term is estimated but not reported for simplicity. Number of observations = 140.

*Indicates statistical significance at 10% level.

**Indicates statistical significance at 5% level.

***Indicates statistical significance at 1% level.

Furthermore, the sizes of the estimate coefficients are in the acceptable ranges. In particular, the ECT term is highly statistically significant and its coefficient, that is, speed of adjustment (SoA) parameter is in the acceptable range. This indicates that the co-integration relationship found among the variables is stable. It also shows that deviations of the dependent variable in the short-run are temporary and can be corrected back to the long-run equilibrium path that it establishes with its explanatory variables.

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renewable energy. Numerically, in 2016, with rising investment in renewable energy, China avoided 1,494 million tonnes emissions, Brazil with 300.6 million tonnes, 180.1 million tonnes by India, 109.1 million tonnes by Russia, and 7.884 million tonnes emissions have been avoided by South Africa (IRENA, R. E. S., 2017).

Lastly, a 1% increase in TFP can reduce the consumption-based CO2 by 0.09% in the long-run according to the estimation results. Negative emissions effects of TFP are theoretically expected as the technological progress, innovations, efficiency, and economies of scale should lead to fewer resources to be consumed in the production of goods and services. Such progress expands the application of efficient production technologies, machines, and equipment as well as efficient home appliances. These result in the rational usage of the resources and less environmental pollution. Our findings for TFP and renewable energy consumption are similar to the outcomes of Khan, Ali, Jinyu, et al. (2020) and Khan, Ali, Umar, et al. (2020).

Hasanov et al. (2018) interpreted that 11 oil-exporting developing countries will produce more emissions over time as the long-run GDP elasticity of the consumption-based CO2 was found to be larger than that of the short-run elasticity. We can extract some useful information by doing the same fashion comparison of the long- and short-run elasticities in Table 5. The estimated long-run the consumption-based CO2 elasticities concerning GDP is slightly smaller than that for the short-run. This finding can be interpreted that in the long-run, the BRICS countries can manage to reduce emissions, or at least to keep it at the same level as today. This also implies that these countries will advance their environmental policies and take efficient measures to reduce CO2. Among other measures to be implemented, from our theoretical framework standpoint, such an achievement can be obtained through technological progress, using more renewable energy in total energy consumption as well as exporting more and importing less CO2 embedded goods and services over the long term. Indeed, the obtained elasticities documented in Table 5 support this interpretation in the sense that the long-term emission reduction effects of the technological innovations, renewable energy consumption, and exports are larger than those in the short-run. It also appears that these countries will import more CO2 contained goods and services over a long time horizon.

6 | CONCLUSION AND POLICY INSIGHTS

This study explores the consumption-based CO2 effects of the technological progress and renewable energy consumption alongside GDP and trade variables for the BRICS countries over the period 1990–2017. Unlike, other existing studies that include variables in their CO2 analysis in ad-hoc manner, we developed a theoretical framework for such an analysis. Also, we accounted for the integration, cointegration, as well as cross-country interdependence and heterogeneity properties of the panel data in the estimations. Therefore, our results are robust and policy insights are well-grounded. We found that the above-mentioned variables can be considered the main determinants of the consumption-based CO2 both in the long- and short-run in the BRICS countries. We estimated that technological progress, renewable energy consumption, and export size contribute to the reduction of CO2 emissions, while GDP and import size increase the pollution.

The findings of this research may provide useful insights for authorities in the formation of technological, energy consumption, and trade-related policies for CO2 emissions. It is common wisdom that technological enhancement and more use of renewable energy consumption are environmentally friendly. Hence, the policymakers in BRICS should continue their supportive measures for the expansion of both components. In addition, they should implement these policies as complementary to each other rather than separate policies. For example, it is well-known that technological innovations and renewable energy are the key components of clean energy transitions. Our empirical finding, that is both technological development and renewable energy consumption in the BRICS nations can reduce CO2 statistically significantly, would encourage decision makers to consider these two components as key factors of the clean energy transition in these countries. We found that an increase in the income level or economic activity will bring more pollution. To compensate this, policymakers may wish to set up some measures and regulations. In this regard, carbon price (CP) is one of the most relevant emission reduction measures as it has several advantages over other measures. Hence, international organizations such as the United Nations, IEA, World Bank (WB), recommend this measure to the authorities of countries all over the world. Hasanov et al. (2020) propose implementation of CP based on the idiosyncratic features of the countries in their policy brief for the G20 group, where BRICS is included. While Klenert et al. (2018) discusses political, cultural, and institutional aspects of this implementation. It would be useful for policy implementations to overview current CP frameworks in BRICS nations. Effective carbon price in Brazil consists entirely of specific taxes on energy use as an explicit carbon tax or an emissions trading system (ETS) is still under consideration but have not been implemented yet. The Brazilian Ministry of Economy announced advances in discussions about carbon pricing on December 23, 2019. Russia has not even considered any explicit CP measure to implement, but it has implemented domestic energy price increases, which can be considered as an implicit CP implementation. The country has substantial energy subsidies as the energy-intensive industry is dominant, while climate conditions require high levels of heating. These make renewables development and CP implementation difficult tasks for the Russian policymakers. Additionally, it is found that removing subsidies would be politically challenging in Russia (Dansie et al., 2010 inter alia). India introduced a nationwide carbon tax of USD1.07/t of CO2 for coal both produced and imported and increased it to USD1.60/t of CO2 in 2014. Since half of India’s electricity generation is produced from coal, it is considerably difficult for the Indian policymakers to implement CP measures. China is in a better position regarding implementation of explicit CP measures compared to any other countries in BRICS although ETS is implemented at pilot level and covers only Beijing, Tianjin, Hubei, Shanghai, Chongqing, Fujian, Shenzhen, and
For example, again, policy measures can be set up amid at increasing ones and compatible with the internationally designed commitments. However, we do not think that such policies are the most effective CO2 contained goods and services and discourage importing of them may recommend policy measures that can encourage exporting more.

The Chinese government also scheduled the implementation of national ETS and started a China-ETS Allowance Allocation and Management Training Series in 31 provinces to build stakeholder capacity and readiness. South African policymakers implemented carbon tax on June 1, 2019, with the first phase from 2019 to 2022 and the second after 2022. The tax rate is US$7/t of CO2 in 2020. This is going to increase until 2022 by 2% and annual consumer price inflation rate, and only inflationary adjustments will be made after 2022 (STCP, 2020).

However, given that explicit CP measure such as ETS requires trading infrastructure, well-designed regulatory framework alongside other foundational elements, implicit CP measures might remain a relevant policy option for those BRICS countries who have not implemented the former one. The revenues collected from the polluted economic activities through CP can be used to finance clean energy transitions. This would be one of the most important measures to implement as it is well-known that the clean energy transitions are very capital intensive and developing countries usually have difficulties in financing it compared to developed ones. One may recommend policy measures that can encourage exporting more CO2 contained goods and services and discourage importing of them as international trade-related emissions policies for the BRICS nations. However, we do not think that such policies are the most effective ones and compatible with the internationally designed commitments. For example, again, policy measures can be set up amid at increasing the exports of goods and services that contain CO2. This can be seen as relevant measures to reduce environmental pollution in BRICS. However, considering that environmental pollution is a global issue, these measures would not be the most effective as they result in more CO2 emissions in the importing countries and consequently more global pollution. Additionally, such measures do not seem to be successfully implemented in the coming decades as countries will implement CO2 border adjustment measures in their international trade in a greater scope. Thus, our main policy recommendations would be the implementations of the measures, regulations, and establishment of the legislative frameworks that support the transition toward renewable energy with technological enhancements.

At the end, we would like to mention two limitations of our study that could encourage future research. Our analysis ends in 2017 because of the data availability. Future research that covers the most recent changes such as oil price drops and COVID-19 recession would be worth considering. Second, as a measure of technological innovations, we use data on the total number of patents. Of course, this is one of the key measures of the innovative activities that can reduce CO2 through advancing production technologies to make them less energy intensive. One also may consider other measures of technological innovations, and research and development expenditures indicator is one of them. This is the frequently used indicator in the empirical studies for the developed economies, but we could not use it because of the data availability as it starts as late as in 2003 for the BRICS from the data sources that are available to us such as WDI.

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ENDNOTES

1 Obviously, Taylor expansion of $\ln(EF+ER)$ will produce $EF+ER+a_0$. Where, $a_0$ is a constant term. We ignored the constant term for simplicity to avoid complications because it does not change the signs of the explana-
tory variables and their functional forms in equation (6).

2 Even if the BRICS countries apply carbon price/tax in their exports and imports, then instead of unity, we will get two constants multiplied to exports and imports shares of GDP. So, the relationship in equation (11) still holds.

3 Note that applying Taylor expansion and ignoring high-order terms and multiplication of the variables, which lead to complicated non-linear relationship in the resulting expression is not new in the literature of CO2 modeling (see e.g., Liddle, 2018b; Mikayilov et al., 2020 inter alia). We again ignored constant terms for simplicity as this ignorance do not change the signs and functional forms of the explanatory variables in equation (15).

4 We use carbon pricing dashboard of WB (https://carbonpricingdashboard.
worldbank.org/map_data). This is the joint efforts of The Partnership for Market Readiness, The Carbon Pricing Leadership Coalition, The Mitigation Action Assessment Protocol and The International Carbon Action Part-
tnership to provide up-to-date information on existing and emerging CP initiatives around the world. We also utilize STCP (2020) in overview of CP policies in BRICS.

REFERENCES

Adebayo, T., Awosusi, A. A., & Adeshola, I. (2020). Determinants of CO2 emissions in emerging markets: An empirical evidence from MINT economies. International Journal of Renewable Energy Development, 9 (3), 411–422. https://doi.org/10.14710/ijred.2020.31321

Adeoyin, F. F., Gumede, M. I., Bekun, F. V., Etokakpan, M. U., & Balsalobre-lorente, D. (2020). Modelling coal rent, economic growth and CO2 emissions: Does regulatory quality matter in BRICS economies? Science of the Total Environment, 710, 136284. https://doi.org/10.1016/j.scitotenv.2019.136284

Ali, S., Dogan, E., Chen, F., & Khan, Z. (2020). International trade and environmental performance in top ten-emitters countries: The role of eco-innovation and renewable energy consumption. Sustainable Development, 28. https://doi.org/10.1002/sd.2153

Alola, A. A., & Kirikkaleli, D. (2019). The nexus of environmental quality with renewable consumption, immigration, and healthcare in the US: Wavelet and gradual-shift causality approaches. Environmental Science and Pollution Research, 26(34), 35208–35217. https://doi.org/10.1007/s11356-019-06522-y

Azevedo, V. G., Sartori, S., & Campos, L. M. S. (2018). CO2 emissions: A quantitative analysis among the BRICS nations. Renewable and Sustainable Energy Reviews, 81(2016), 107–115. https://doi.org/10.1016/j. rerse.2017.07.027

Bai, J., & Carrion-i-Silvestre, J. L. (2009). Testing panel cointegration with unobservable dynamic common factors, MPRA Paper, University
Franzen, A., & Mader, S. (2018). Consumption-based versus production-based carbon dioxide emissions in G-7 nations. Energy Economics, 89, 104806. https://doi.org/10.1016/j.eneco.2020.104806

Khan, Z., Ali, S., Umar, M., Krikikalil, D., & Jiao, Z. (2020). Consumption-based carbon emissions and international trade in G7 countries: The role of environmental innovation and renewable energy. Science of the Total Environment, 65, 138945. https://doi.org/10.1016/j.scitotenv.2020.138945

Klener, D., Mattauch, L., Commet, E., Edenhoder, O., Hepburn, C., Rafaty, R., & Stern, N. (2018). Making carbon pricing work for citizens. Nature Climate Change, 8(8), 669–677.

Knight, K. W., & Schor, J. B. (2014). Economic growth and climate change: a cross-national analysis of territorial and consumption-based carbon emissions in high-income countries. Sustainability, 6(6), 3722–3731.

Liddle, B. (2018a). Consumption-based accounting and the trade-carbon emissions nexus. Energy Economics, 69, 71–78.

Liddle, B. (2018b). Consumption-based accounting and the trade-carbon emissions nexus in Asia: A heterogeneous, common factor panel analysis. Sustainability, 10(10).

Liddle, B., & Hasanov, F. J. (2020). Industry Electricity Price and Output Elasticities: An OECD & non-OECD Country Common Factor Dynamic Panel Analysis. USAEE Working Paper No. 20-434.

Micoskey, S., & Kao, C. (1998). A residual-based test of the null of cointegration in panel data. Econometric Reviews, 17(1), 57–84.

Mi, Z., Zheng, J., Meng, J., Zheng, H., Li, X., Coffman, D. M., ... Guan, D. (2019). Carbon emissions of cities from a consumption-based perspective. Applied Energy, 235(2018), 509–518. https://doi.org/10.1016/j.apenergy.2018.10.137

Micheika, N. M., Fletcher, J., & Burnett, W. (2013). An empirical analysis of the role of China’s exports on CO2 emissions. Applied Energy, 104, 258–267.

Mikayilov, J. I., Mukhtarov, S., Mammadov, J., & Aliyev, S. (2020). Environmental consequences of tourism: do oil-exporting countries import more CO2 emissions?. Energy Sources, Part B: Economics, Planning, and Policy, 1–14.

Mikayilov, J. I., & Hasanov, F. J. (2019). Total Factor Productivity and Energy Consumption: Theoretical Reconsideration. Pre-print by advance.sagepub.com.

Negro, S. O., & Hekkert, M. P. (2008). Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany. Technology Analysis & Strategic Management, 20(4), 465–482.

Nordhaus, W. (1975). The demand for energy: an international perspective. Cowles Foundation, Discussion paper no 405.

Pedroni, P. (2004). Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. Econometric Theory, 597–625.

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. Journal of Applied Econometrics, 22(2), 265–312.

Pesaran, M. H. (2015). Testing weak cross-sectional dependence in large panels. Econometric Reviews, 34(6–10), 1089–1117.

Pesaran, M. H., & Yamagata, T. (2008). Testing slope homogeneity in large panels. Journal of Econometrics, 142(1), 50–93.

Peters, G. P., Minx, J. C., Weber, C. L., & Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. Proceedings of the National Academy of Sciences, 108(21), 8903–8908.
Santra, S. (2017). The effect of technological innovation on production-based energy and CO2 emission productivity: evidence from BRICS countries. *African Journal of Science, Technology, Innovation and Development*, 9(5), 503–512.

Sebri, M., & Ben-Salha, O. (2014). On the causal dynamics between economic growth, renewable energy consumption, CO2 emissions and trade openness: Fresh evidence from BRICS countries. *Renewable and Sustainable Energy Reviews*, 39, 14–23. https://doi.org/10.1016/j.rser.2014.07.033

Shirani-Fakhr, Z., Khoshakhlagh, R., & Sharifi, A. (2015). Estimating Demand Function for Electricity in Industrial Sector of Iran Using Structural Time Series Model (STSM). *Applied Econometrics and International Development*, 15(1), 143–160.

Simoes, A. J. G., & Hidalgo, C. A. (2011). The economic complexity observatory: An analytical tool for understanding the dynamics of economic development. Workshops at the twenty-fifth AAAI conference on artificial intelligence.

Solow, R. M. (1957). Technical change and the aggregate production function. *The Review of Economics and Statistics*, 39(3), 312–320.

STCP (2020). State and Trends of Carbon Pricing 2020. *World Bank Group*. Washington DC.

Steinberger, J. K., Roberts, J. T., Peters, G. P., & Baiocchi, G. (2012). Pathways of human development and carbon emissions embodied in trade. *Nature Climate Change*, 2(2), 81–85.

Su, C. W., Naqvi, B., Shao, X. F., Li, J. P., & Jiao, Z. (2020). Trade and technological innovation: The catalysts for climate change and way forward for COP21. *Journal of Environmental Management*, 269, 110774. https://doi.org/10.1016/j.jenvman.2020.110774

Suurs, R. A., & Hekkert, M. P. (2009). Cumulative causation in the formation of a technological innovation system: The case of biofuels in the Netherlands. *Technological Forecasting and Social Change*, 76(8), 1003–1020.

Swamy, P. A. (1970). Efficient inference in a random coefficient regression model. *Econometrica: Journal of the Econometric Society*, 311–323.

United Nation (UN). (2017). Retrieved from https://www.un.org/en/Wang, Z., Zhang, B., & Wang, B. (2018). The moderating role of corruption between economic growth and CO2 emissions: Evidence from BRICS economies. *Energy*, 148, 506–513.

Wen, W., & Wang, Q. (2020). Re-examining the realization of provincial carbon dioxide emission intensity reduction targets in China from a consumption-based accounting. *Journal of Cleaner Production*, 244, 118488. https://doi.org/10.1016/j.jclepro.2019.118488

Westerlund, J. (2005). New simple tests for panel cointegration. *Econometric Reviews*, 24(3), 297–316.

Westerlund, J., & Edgerton, D. L. (2007). A panel bootstrap cointegration test. *Economics Letters*, 97(3), 185–190.

Westerlund, J., & Edgerton, D. L. (2008). A simple test for cointegration in dependent panels with structural breaks. *Oxford Bulletin of Economics and Statistics*, 70(5), 665–704.

Wiebe, K. S., & Yamano, N. (2016). Estimating CO2 emissions embodied in final demand and trade using the OECD ICIO 2015: Methodology and results.

World Bank (WB). (2019). *World development indicators (WDI) 2019*. The World Bank.

Zakarya, G. Y., Mostefa, B., Abbes, S. M., & Seghir, G. M. (2015). Factors affecting CO2 emissions in the BRICS countries: A panel data analysis. *Procedia Economics and Finance*, 26, 114–125. https://doi.org/10.1016/s2212-5671(15)00890-4

Zeng, S., Liu, Y., Liu, C., & Nan, X. (2017). A review of renewable energy investment in the BRICS countries: History, models, problems and solutions. *Renewable and Sustainable Energy Reviews*, 74, 860–872.

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