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RESEARCH ARTICLE

Nexus among the hydropower energy consumption, economic growth, and CO_2 emissions: evidence from BRICS countries

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Abstract

The present paper investigates the effects of hydropower energy consumption on economic growth and CO_2 emissions in the BRICS countries, spanning the period 1990–2016. To achieve this aim of the study, we employ the panel autoregressive distributed lag (ARDL) model and panel quantile regression (PQR) estimations. The results confirm that hydropower energy consumption has a positive association with economic growth in the long run and short run, and negative association with CO_2 emissions in the long run. Further, our panel quantile regression showed that the effects of independent variables on economic growth and CO_2 emissions are heterogeneous across the quantiles. Specifically, the effect of hydropower energy use significantly promotes economic growth across all quantiles (expect 10th quantile), while hydropower energy use has a negative and positive impact on CO_2 emissions in the lower and higher quantiles, respectively. Given these findings, our study offers substantial value to empirical literature and also provides important policy implications.

Keywords Hydropower energy · Economic growth · CO_2 emissions · BRICS countries

JEL Classification Q42 · Q43 · Q53 · C33

Introduction

In recent years, there is a growing concern among the environmental scientists and policymakers on energy transformation from conventional sources to non-conventional energy sources. Because, climate change and greenhouse gas (GHG) emissions are indisputable facts, which are mainly caused by human activities and combustion of fossil fuels. Therefore, most of the countries in the world have gradually reduced reliance on fossil fuels and sought for renewable and clean energy sources which mitigate CO_2 emissions. Most recently, in the Republic of South Korea, the United Nations Intergovernmental Panel on Climate Change (IPCC) report highlights that limit the increase in the global average temperature to 1.5 °C. In order to restrict it, coal-fired electricity must end by 2050. According to IPCC (2011), it is predicted that about 80% of the global total primary energy supplied by renewable sources in 2050. Hydropower is one of the main faster-growing source forms of renewable energy. It provides 40% and 75% of share in total renewable energy generation in both the developed and developing countries during 2012–2040 (IEO 2016). It clearly indicates the development of hydropower energy in developing countries, especially in BRICS nations. Therefore, hydropower energy consumption can give a solution to climate change and GHG emission.

Over the past, the BRICS countries have been the fastest-growing emerging economies in the world. In 2015, the BRICS countries accounted for 30.8% and 42% of global GDP and world population, respectively. Simultaneously, this group consumed 37% of the total world energy, while they are responsible for 41.4% of global CO_2 emissions. Furthermore, these countries have heavily relied on fossil fuel energy sources; hence, 71% of their total energy generation come from fossil fuels only (BRICS Energy Indicators 2015).

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However, these economies are shifting their energy use from fossil fuel to renewable sources to mitigate greenhouse gas emissions. Further, investment in renewable energy sources is significantly growing in the BRICS countries[1]. Therefore, a massive amount of installed capacity has been increasing. Top six countries together accounted for 63% of total global hydropower installed capacity in 2015[2]. Among the six countries, four countries are from the BRICS countries. More precisely, this group of countries accounts for 45% of the world's total hydropower generation. Therefore, we argue that increasing the share of hydropower energy not only combats CO_2 emissions but also meets the demand for energy. Then, the main aim of our study is to answer the following question: First, Is economic growth positively affected by hydropower energy consumption? Second, Do CO_2 emissions decrease by the use of hydropower energy?

Given the above background, it is important to empirically investigate the nexus among the hydropower energy use, economic growth, and CO_2 emissions in the BRICS countries because empirical results invoke essential policy implications for energy economists and policymakers. However, in the literature, there are not many studies which have probed the nexus among hydropower energy use, economic growth, and CO_2 emissions, for example, Bildirici (2014) in 15 countries, Lau et al. (2016) in Malaysia, Bildirici and Gökmenoğlu (2017) in G7 countries, Solarin et al. (2017) in India and China, and Ummalla and Samal (2018) in China. More specifically, this is the first study to explore the nexus among the hydropower energy use, economic growth, and CO_2 emissions in the case of BRICS countries. Given the scarce literature on the BRICS regarding this issue, the present study aims to fill this research gap by employing more recent longer dataset, a more robust model, and appropriate panel modelling techniques.

The contribution of this study is fivefold. First, to the best of our knowledge, this is the first piece of study that empirically explores the nexus among the hydropower energy consumption, economic growth, and CO_2 emissions in the BRICS countries. Second, most of the previous studies have used time series data for empirical investigation among these three variables. However, we use panel data to explore nexus among the variables which provide the more accurate estimation of model parameters with more degrees of freedom and less multicollinearity, and more temporal and dynamics of relationship which cannot be addressed by a single time series data (Hsiao 2007). Third, due to financial integration and globalization, macroeconomic variables are strongly cross-sectional dependent (Banerjee et al. 2004; Paramati et al. 2016). Furthermore, the traditional panel data estimators such as random and fixed effects are inconsistent and give invalid inference in the presence of cross-sectional dependence. To overcome this problem, we apply cross-sectional dependence (CD) test developed by Pesaran (2004). Fourth, conventional unit root tests provide inappropriate results due to low power when they are used on a series which is cross-sectional dependent. Therefore, this study applies Pesaran's (2007) cross-sectional augmented ADF (CADF) panel unit root test and cross-sectional IPS (CIPS) panel unit root test which assume cross-section dependence. Fifth, this study utilizes the panel autoregressive distributed lag (ARDL) model to examine the short-run and long-run relationships among the variables. Finally, it employs the panel quantile regression to investigate the impact of independent variables on economic growth and CO_2 emissions at their different quantile levels.

The main findings of our study illustrate that hydropower energy consumption, CO_2 emissions, and population have a positive impact on economic growth. However, hydropower energy consumption and population have a negative impact on CO_2 emissions, while economic growth positively contributes to CO_2 emissions in the long run. In the short run, hydropower energy consumption has a positive association with economic growth, while hydropower energy consumption and population have a negative association with CO_2 emissions, and economic growth has a positive impact on it at the insignificant level. Furthermore, our panel quantile regression results indicate that the effects of independent variables on economic growth and CO_2 emissions are heterogeneous across the quantiles.

The rest of the paper is structured as follows. The "Review of the Literature" section includes a review of the literature. The "Data and methodology" section explains the nature of data, their measurement, and the empirical methodology. The "Empirical results and analysis" section presents empirical findings and its analysis. The "Conclusion and policy implications" section offers the conclusion and its policy implications.

Review of the literature

There are numerous studies which have investigated the linkages among energy use, economic growth, and CO_2 emissions across the globe. Alam and Paramati (2015) examined the nexus among oil consumption, economic growth, and CO_2 emissions in 18 major oil-consuming developing countries, spanning the period 1980–2012. They found bidirectional causality among the selected variables in the short run and

[1] During the Six BRICS Summit, held in Brazil in July 2014, the delegates from the BRICS countries highlighted that financial and energy security were the main agenda. Accordingly, the member countries are signed on the establishment of "BRICS development bank" and "BRICS energy association." The main aim of the bank is to mobilize financial recourses for infrastructure and sustainable energy development, and the energy association will work on the creation of "fuel reserve bank" and "energy policy institute" for the member countries.

[2] Those countries are China (27.9%), Brazil (8.6%), USA (7.5%), Canada (7.4%), Russia (4.5%), and India (4.4%).

long run. Alam et al. (2017) investigated the relationship among natural gas consumption, trade openness, and economic growth in 15 top natural gas–consuming developing countries during 1990–2012. They reported that natural gas consumption and trade openness have a positive impact on economic growth. Further, they found bidirectional causality among these three variables. Alam et al. (2018) probed the nexus between access to electricity and labor productivity in 56 developing countries covering the period 1991–2013. They reported that access to electricity and economic growth have a positive impact on labor productivity. Finally, they found bidirectional causality among access to electricity, labor productivity, and economic growth in their analysis. Similarly, many studies have conducted on the relationship among renewable energy use, economic growth, and CO_2 emissions. However, the findings of the studies are diverse across countries using different econometric methods and datasets for both the time-series and panel studies. For example, Sadorsky (2009) investigated the nexus between renewable energy consumption and real income in 18 emerging market economies during 1994–2003. The results indicated that real income has a positive association with renewable energy use. Similarly, Lin and Moubarak (2014) reported that an increase in economic growth promotes renewable energy use in China, spanning the period 1977–2011. The results also established bidirectional causal relationship between renewable energy use and economic growth, whereas Apergis and Payne (2010a) demonstrated that renewable energy use has a positive and significant impact on economic growth in 20 OECD countries during 1985–2005. Further, they reported that there exists a bidirectional causal relationship between renewable energy consumption and economic growth. Other studies by Apergis and Payne (2010b, 2011) also established similar conclusions in the case of 13 Eurasian countries and 6 Central American countries, respectively. Further, Salim et al. (2014) argued that an increase in renewable energy consumption boosts economic growth in 29 OECD countries during 1980–2011. Their results concluded that unidirectional causal linkages exist from economic growth to renewable energy consumption. Shahbaz et al. (2015) revealed that renewable energy consumption promotes economic growth in Pakistan over the period 1972Q1–2011Q4. The Granger causality test revealed bidirectional causal relationship between these variables. Bhattacharya et al. (2016) examined the relationship between renewable energy consumption and economic growth from the top 38 countries over the period 1991–2012. The long-run estimates revealed that renewable energy use has a positive association with economic growth. Inglesi-Lotz (2016) argued that renewable energy consumption plays a positive and significant role in promoting economic growth in 34 OECD economies during 1990–2010. Gozgor (2016) confirmed the presence of convergence in renewable energy consumption in the case of China and India while divergence in the case of Brazil during 1971–2014. Koçak and Şarkgüneşi (2017) examined the nexus between renewable energy consumption and economic growth in 9 Black Sea and Balkan countries during 1990–2012. The authors reported that renewable energy consumption induces economic growth. Further, the study also confirmed the two-way causal relationship between these variables. Ito (2017) investigated the nexus among CO_2 emissions, renewable and non-renewable energy consumption, and economic growth in 42 developed economies during 2002–2011. The results showed that renewable energy consumption increases economic growth and reduces CO_2 emissions in the long run. Paramati et al. (2017b) revealed that an increase in the use of renewable energy is positively associated with economic growth and negatively with CO_2 emissions in the G20 nations during 1991–2012.

By contrast, Marques and Fuinhas (2012) argued that renewable energy consumption has a negative impact on economic growth in 24 European countries, spanning the period 1990–2007. Ocal and Aslan (2013) also found that renewable energy use retards economic growth in Turkey during 1990–2000. Further, they also found unidirectional causal linkages from economic growth to renewable energy consumption. Dogan (2015) documented that non-renewable energy consumption increases economic growth while renewable energy consumption reduces economic growth in Turkey, although insignificant in the long run during 1990–2012. Further, the author also established one-way causal linkage running from renewable energy consumption to economic growth, while two-way causal linkages are established between non-renewable energy consumption and economic growth in the long run. Bhattacharya et al. (2017) documented that renewable energy consumption promotes economic growth in 85 developed and developing economies during the period 1991–2012. However, Menegaki (2011) could not find any causal linkage between renewable energy consumption and growth in 27 European countries during 1997–2007. Again, Ben Aïssa et al. (2014) examined the nexus between output, renewable energy consumption, and economic growth in 11 African countries during 1980–2008. The authors also reported that no causal nexus is detected between renewable energy consumption and economic growth. Kutan et al. (2018) revealed that no causality is found between renewable energy use and economic growth in 4 major emerging market economies, namely, Brazil, India, China, and South Africa during 1990–2012. Similarly, Paramati et al. (2018) also revealed similar results in 17 countries from the G20 nations, spanning the period 1980–2012. Recently, Gozgor (2018) and Gozgor et al. (2018) reported that renewable energy use has a positive association with economic growth in the USA and 27 OECD countries, respectively. Most recently, Ummalla and Samal (2019) documented unidirectional Granger causality from renewable energy use to economic growth in India, while no causality found in China in the short run. Further, in the long run, they found bidirectional causality between these two variables in both China and India, spanning the period 1965–2016.

Hydropower energy consumption and economic growth

Many studies have devoted to examining the nexus between renewable energy consumption and economic growth in the literature. However, a minuscule amount of studies have been conducted on the nexus between hydropower energy consumption and economic growth in the world. For example, Abakah (1993) probed the linkages between three disaggregate sources of energy, i.e., charcoal, petroleum, and hydroelectricity consumption, with economic growth in Ghana during 1976–1990. The empirical results showed that hydroelectricity and petroleum consumption have a positive association with economic growth in the short run and long run, while charcoal consumption has a negative association with economic growth. Okafor (2012) examined the linkages among the selected disaggregate energy, i.e., coal, hydro, and oil consumption and economic growth in Nigeria and South Africa, spanning the period 1970–2010. The results of the Granger causality test indicated that coal consumption and economic growth are Granger causes in South Africa, while coal consumption Granger causes economic growth in Nigeria. However, hydropower energy use and economic growth Granger causes each other in Nigeria and South Africa. Ziramba (2013) proved the nexus between hydroelectricity consumption and economic growth in three African countries, namely, Egypt, South Africa, and Algeria, over the period 1980–2009. Their findings indicated that hydroelectricity consumption promotes economic growth in both Egypt and South Africa. The author also found that hydroelectricity consumption and economic growth are Granger causes to each other in Algeria, while economic growth Granger causes hydroelectricity consumption in South Africa. However, no causal linkage is detected between hydroelectricity consumption and economic growth in Egypt. Ohler and Fetters (2014) reported that hydroelectricity consumption positively contributes to economic growth in 20 OECD countries during 1990–2008. Further, Granger causality test results documented hydroelectricity consumption and economic growth Granger causes to each other in both the short run and long run. Solarin and Ozturk (2015) investigated the causal linkages between hydroelectricity consumption and economic growth in seven Latin American countries during 1970–2012. The long-run estimates of without structural break revealed that hydroelectricity consumption has positively associated with economic growth in Brazil, Peru, and Venezuela, while negatively in Colombia and Ecuador. However, hydroelectricity consumption promotes economic growth for all the countries except Venezuela with two structural break analyses. Their causality test results without break revealed hydroelectricity consumption Granger causes economic growth for all the six countries except Chile in the long run. Their findings from two structural break analyses confirmed hydroelectricity consumption and economic growth are Granger causes each other in Argentina and Venezuela, whereas hydroelectricity consumption Granger causes economic growth in Brazil, Chile, Colombia, Ecuador, and Peru, respectively. Apergis et al. (2016) reported that economic growth promotes hydroelectricity consumption in the top 10 hydroelectricity-consuming countries. The Granger causality test results indicated economic growth Granger causes hydroelectricity consumption in the pre-1988 period, whereas hydroelectricity consumption and economic growth are Granger causes each other in the post-1988 period in both the short run and long run. They suggested that bidirectional linkage not only was established between hydroelectricity consumption and economic growth but also created a more significant impact on economic growth via the increasing role of hydroenergy source for the break years 2000 and 2009. Bildirici (2016) examined the nexus between hydropower energy consumption and economic growth in OECD and non-OECD high-income countries, spanning the period 1980–2011. The empirical results confirmed that hydropower energy consumption reduces economic growth in Brazil, Canada, Finland, Mexico, and the USA, while increases economic growth in Turkey. The results of the Granger causality test revealed that hydropower energy consumption Granger causes economic growth in OECD countries with high income. Further, in the short run, the study also found that economic growth Granger causes hydropower energy consumption in Brazil, the USA, Finland, Mexico, and Turkey. Finally, the author detected hydroelectricity consumption and economic growth are Granger causes each other in the long run.

Hydropower energy consumption, economic growth, and CO_2 emissions

In the literature, there is evolving concern regarding the nexus between hydropower energy consumption and economic growth. However, investigating the impact of hydropower energy use on CO_2 emissions is very scarce, although hydropower use can improve the environmental quality. In recent years, a minuscule amount of available literature probed the relationship among the hydropower energy consumption, economic growth, and CO_2 emissions in the developed and developing countries. For instance, Bildirici (2014) explored the linkages among the hydropower energy consumption, environmental pollution, and economic growth in 15 countries. The results from the Toda-Yamamoto causality test revealed unidirectional causality running from hydropower energy consumption to economic growth in Austria, from economic growth to hydropower energy consumption in Germany, and an absence of any causality between hydropower energy consumption and economic growth in the UK. However, bidirectional causality is established between hydropower energy consumption and economic growth in the rest of the countries. Furthermore, the author also found no causality between hydropower energy consumption and CO_2 emissions in Belgium, Iceland, and the UK, while a unidirectional causality exists from CO_2 emissions to hydropower energy consumption in the rest of the countries. Further, Lau et al. (2016) explored the nexus among the hydroelectricity consumption, economic growth, and CO_2 emissions in Malaysia, spanning the period 1965–2010. The short-run results revealed that unidirectional causal linkage exists from hydroelectricity consumption to CO_2 emissions. However, in the long run, unidirectional causality runs from economic growth and hydroelectricity consumption to CO_2 emissions. Bildirici and Gökmenoğlu (2017) investigated the relationship among hydropower energy consumption, economic growth, and CO_2 emissions in G7 countries during 1961–2013. Their empirical results revealed unidirectional causality running from hydropower energy consumption to economic growth in overall and bidirectional causality between hydropower energy consumption to economic growth in few G7 countries. The authors also detected CO_2 emissions Granger causes hydropower energy consumption in the first, second, and third regimes, while hydropower energy consumption Granger causes CO_2 emissions in some of the G7 countries. Recently, Solarin et al. (2017) examined the linkages among the hydroelectricity consumption, urbanization, economic growth, and CO_2 emissions in India and China during 1965–2013. Their long-run results revealed that economic growth and urbanization have a positive association with CO_2 emissions, while hydroelectricity consumption has a negative association on it in both India and China. The findings from the Granger causality test showed that there exists a unidirectional causality running from hydroelectricity consumption to CO_2 emissions, from economic growth to hydroelectricity consumption, and from hydroelectricity consumption to CO_2 emissions in the short run. However, a bidirectional causality is established between hydroelectricity consumption and CO_2 emissions and hydroelectricity consumption and economic growth in both India and China in the long run. Furthermore, the authors also found the presence of environmental Kuznets curve (EKC) in both countries. Most recently, Ummalla and Samal (2018) documented that hydropower energy consumption increases economic growth and reduces CO_2 emissions in the long run. Their empirical results confirmed unidirectional causality running from hydropower energy consumption to economic growth in the short run, while bidirectional causality among the hydropower energy consumption, economic growth, and CO_2 emissions in the long run. However, they did not find the existence of EKC in China during 1965–2016.

Based on the above literature, it was confirmed that empirical results differ regardless of the country selection, the data period, the frequency of observations, and the econometric techniques of probing the nexus among variables. However, there are hardly any studies which have investigated the linkages among hydropower energy consumption, economic growth, and CO_2 emissions in a time-series framework. To the best of our knowledge, this is the first study which explores the nexus among hydropower energy consumption, economic growth, and CO_2 emissions in a panel of BRICS countries, spanning the period 1990–2016.

Data and methodology

Data

The present study used yearly data for the BRICS countries (namely Brazil, Russia, India, China, and South Africa) during 1990–2016. The considered variables of the present study include per capita hydropower (HYD) energy consumption in million tons oil equivalent (Mtoe), per capita GDP (GDP) (constant 2010 US$), per capita carbon dioxide (CO_2) emissions in million metric tons. The data on HYD and CO_2 are obtained from the BP Statistical Review of World Energy 2017, whereas population and GDP data are retrieved from the World Development Indicators (WDI) online database. All the selected variables are transferred into natural logarithms.

Methodology

The main objective of the study is to investigate the short-run and long-run nexus among the hydroelectricity, economic growth, and CO_2 emissions in the BRICS countries. To fulfil the objective, our study employs the panel ARDL bounds testing approach. Further, panel quantile regression was applied to probe the effects of independent variables on economic growth and CO_2 emissions at their different quantile levels. The simple framework of the model can be written as follows:

$$\mathrm{lnGDP}_{it} = \alpha_1 + \beta_1 \mathrm{lnHYD}_{it} + \beta_2 \mathrm{lnCO}_{2it} + \beta_3 lnPOP_{it} + e_{1it} \quad (1)$$

$$\mathrm{lnCO}_{2it} = \alpha_2 + \beta_4 \mathrm{lnHYD}_{it} + \beta_5 \mathrm{lnGDP}_{it} + \beta_6 lnPOP_{it} + e_{2it} \quad (2)$$

where GDP_{it}, HYD_{it}, CO_{2it}, and POP_{it} denote per capita GDP, per capita hydropower energy consumption, per capita CO_2 emissions, and population, respectively. The subscript i ($i = 1 \ldots. N$) and $t(t = 1 \ldots. T)$ represent country and time period, respectively. Finally, e_{1it} and e_{2it} are the two residual terms which are assumed to be normally distributed.

Cross-sectional dependence

We first aim to identify whether the given series is cross-sectional dependent or independent. Heterogeneity may exist across the countries for the considerable variables. Therefore, the prerequisite panel econometric tests are required before commencing analysis[3]. Henceforth, this study employs Pesaran's (2004) cross-sectional dependence (CD) test which takes into account both issues. The null hypothesis of cross-sectional independence is tested against the alternative hypothesis of cross-sectional dependence. If we reject the null hypotheses, it suggests that there is a presence of cross-sectional dependence among all of the variables.

Panel unit root tests

With the existence of cross-sectional dependence, we did not apply the first-generation unit root tests such as IPS and LLC because it does not address the issue of cross-sectional dependence. Therefore, we employ the Pesaran (2007) CADF and CIPS panel unit root tests in our analysis. It is worth noting that both of these panel unit root tests produce more reliable and accurate results in the presence of both cross-sectional dependence and heterogeneity across the sample countries[4]. These unit root tests were used to verify the order of integration among the variables. The null hypothesis of a unit root is tested against the alternative hypothesis of no unit root.

Panel ARDL model

In this paper, we apply the panel ARDL model with a country fixed effect and the period fixed effect propounded by Pesaran et al. (1999) to investigate the short-run and long-run relationship among the hydropower energy consumption, economic growth, CO_2 emissions, and population in the BRICS countries. This method also helps to estimate the consistent and efficient estimators by eliminating the problem of endogeneity. The specified model can be written as follows:

$$\begin{aligned}\Delta \mathrm{lnGDP}_{it} = {} & \delta_0 + \sum_{i=1}^{q} \delta_{1i}\Delta lnGDP_{i,t-1} + \sum_{i=1}^{q} \delta_{2i}\Delta lnHYD_{i,t-1} \\ & + \sum_{i=1}^{q} \delta_{3i}\Delta lnCO_{2i,t-1} + \sum_{i=1}^{q} \delta_{4i}\Delta lnPOP_{i,t-1} \\ & + \delta_5 \mathrm{lnGDP}_{i,t-1} + \delta_6 \mathrm{lnHYD}_{i,t-1} \\ & + \delta_7 \mathrm{lnCO}_{2i,t-1} + \delta_8\, lnPOP_{i,t-1} + e_{1it} \end{aligned} \tag{3}$$

$$\begin{aligned}\Delta \mathrm{lnCO}_{2it} = {} & \beta_0 + \sum_{i=1}^{q} \beta_{1i}\Delta lnCO_{2i,t-1} + \sum_{i=1}^{q} \beta_{2i}\Delta lnHYD_{i,t-1} \\ & + \sum_{i=1}^{q} \beta_{3i}\Delta lnGDP_{i,t-1} + \sum_{i=1}^{q} \beta_{4i}\Delta lnPOP_{it-1} \\ & + \beta_5 \mathrm{lnCO}_{2i,t-1} + \beta_6 \mathrm{lnHYD}_{i,t-1} \\ & + \beta_7 lnGDP_{i,t-1} + \beta_8 lnPOP_{i,t-1} + e_{2it} \end{aligned} \tag{4}$$

where q is the lag order, e_{1it} and e_{2it} are the error terms which are assumed to be identically and independently distributed. Equations (3) and (4) can be transformed into an error correction model (ECM) to Eqs. (5) and (6) as follows:

$$\begin{aligned}\Delta \mathrm{lnGDP}_{it} = {} & \delta_0 + \sum_{i=1}^{q} \delta_{1i}\Delta lnGDP_{i,t-1} + \sum_{i=1}^{q} \delta_{2i}\Delta lnHYD_{i,t-1} + \sum_{i=1}^{q} \delta_{3i}\Delta lnCO_{2i,t-1} + \sum_{i=1}^{q} \delta_{4i}\Delta lnPOP_{i,t-1} \\ & + \xi\left(\mathrm{lnGDP}_{i,t-1} + \pi_1 \mathrm{lnHYD}_{i,t-1} + \pi_2 \mathrm{lnCO}_{2i,t-1} + \pi_3 lnPOP_{i,t-1}\right) + e_{1it} \end{aligned} \tag{5}$$

$$\begin{aligned}\Delta \mathrm{lnCO}_{2it} = {} & \beta_0 + \sum_{i=1}^{q} \beta_{1i}\Delta lnCO_{2i,t-1} + \sum_{i=1}^{q} \beta_{2i}\Delta lnHYD_{i,t-1} + \sum_{i=1}^{q} \beta_{3i}\Delta lnGDP_{i,t-1} + \sum_{i=1}^{q} \beta_{4i}\Delta lnPOP_{it-1} \\ & + \xi\left(\mathrm{lnCO}_{2i,t-1} + \theta_1 \mathrm{lnHYD}_{i,t-1} + \theta_2 lnGDP_{i,t-1} + \theta_3 lnPOP_{i,t-1}\right) + e_{2it} \end{aligned} \tag{6}$$

where ξ is the speed of the adjustment parameter. π_1, π_2, and π_3 are the long-run coefficients of per capita hydropower energy consumption, per capita CO_2 emissions, and population, respectively in Eq. (5), while θ_1, θ_2, and θ_3 are the long-run coefficients of per capita hydropower energy consumption, per capita GDP, and population, respectively, in Eq.

[3] Several authors (e.g., Alam et al. 2015; Alam et al. 2017; Paramati et al. 2016; Paramati et al. 2017a) argue the cross-sectional dependence and heterogeneity in their analysis.

[4] The previous studies (e.g., Dogan et al. 2017; Mallick et al. 2016; Paramati et al. 2017a) used the CADF and CIPS cross-sectional unit root tests in their empirical analysis.

(6). γ_{1i}, γ_{2i}, γ_{3i}, and γ_{4i} and α_{1i}, α_{2i}, α_{3i}, and α_{4i} denote the short-run coefficients in Eqs. (7) and (8). Therefore, the panel ARDL (p, q, k, and g) models are written as:

$$\Delta \ln GDP_{it} = \gamma_0 + \sum_{i=1}^{p} \Delta\gamma_{1i}\Delta lnGDP_{i,t-1} + \sum_{i=1}^{q} \Delta\gamma_{2i}\Delta lnHYD_{i,t-1} + \sum_{i=1}^{k} \Delta\gamma_{3i}\Delta lnCO_{2i,t-1} + \sum_{i=1}^{g} \Delta\gamma_{4i}\Delta lnPOP_{i,t-1} + \xi\left(\ln GDP_{i,t-1} + \pi_1 \ln HYD_{i,t-1} + \pi_2 \ln CO_{2i,t-1} + \pi_3 lnPOP_{i,t-1}\right) + e_{1it} \quad (7)$$

$$\Delta \ln CO_{2it} = \alpha_0 + \sum_{I=1}^{p} \Delta\alpha_{1i}\Delta lnCO_{2i,t-1} + \sum_{i=1}^{q} \Delta\alpha_{2i}\Delta lnHYD_{i,t-1} + \sum_{i=1}^{k} \Delta\alpha_{3i}\Delta lnGDP_{i,t-1} + \sum_{i=1}^{g} \Delta\alpha_{4i}\Delta lnPOP_{it-1} + \xi\left(\ln CO_{2i,t-1} + \theta_1 \ln HYD_{i,t-1} + \theta_2 lnGDP_{i,t-1} + \theta_3 lnPOP_{i,t-1}\right) + e_{2it} \quad (8)$$

Panel quantile regression

We have applied the fixed effect panel quantile regression model to explore the impact of hydropower energy use on economic growth and CO_2 emissions in the BRICS countries throughout the conditional distribution. The advantages of the panel quantile regression model are as follows: (a) it is an extension of classical ordinary least square (OLS) method of conditional mean which enables to estimate with different points of conditional probability distribution of dependent variables. (b) This method also takes into account the heterogeneous structure of the different levels of growth and CO_2 emissions as the OLS does not consider it. (c) It minimizes the problem of outlier observations and issues related to heavy distributions. (d) It is a more efficient method than the ordinary least square (OLS) estimators if the error terms are not normally distributed. (e) It enables us to assess the conditional heterogeneous covariance effects of CO_2 emissions and economic growth. (f) It also helps to investigate the impact of the hydropower energy consumption on economic growth and CO_2 emissions at different levels of the conditional distribution of the dependent variables. In quantile regression, the conditional distribution of dependent variable is divided into different quantiles, where the 50th quantile represents the median (Hübler 2017). Therefore, we can represent the τth quantile as the conditional distributions of dependent variables (per capita economic growth and CO_2 emissions), and given the set of independent variables X_{it}, the equation can be specified as:

$$Q_\tau\left(\frac{lnGDP_{it}}{X_{it}}\right) = \alpha_\tau + \beta_\tau X_{it} + \alpha_\tau \mu_{it} \quad (9)$$

$$Q_\tau\left(\frac{lnCO_{2,it}}{X_{it}}\right) = \alpha_\tau + \beta_\tau X_{it} + \alpha_\tau \mu_{it} \quad (10)$$

where, in Eqs. (9) and (10), $\ln GDP_{it}$ and $\ln CO_{2,\ it}$ are the natural logarithms of per capita economic growth and CO_2 emissions of country i in time period t, and X_{it} denotes the vector of three independent variables, namely, per capita hydropower energy consumption, CO_2 emissions, and population, respectively, and vice versa for Eq. (10). u_{it} represents unobservable factors. The coefficients in Eqs. (9) and (10) are estimated minimizing the absolute value of residuals by using the following objective functions:

$$Q_\tau(\beta_\tau) = \min_\beta \sum_{i=1}^{n} \left[\left|lnGDP_{it} - \beta_\tau X_{it}\right|\right] = \min_\beta \left[\sum_{i:lnGDP_{it} \geq \beta X_i}^{n} \tau\left|lnGDP_{it} - \beta_\tau X_{it}\right| + \sum_{i:lnGDP_{it} < X_{it}}^{n} (1-\tau)\left|lnGDP_{it} - \beta_\tau X_{it}\right|\right] \quad (11)$$

The same procedure follows when the CO_2 emission is a dependent variable. Koenker (2004) estimated the vector of individual effects using shrinkage methodology which does not capture the unobserved factors with fixed effects regression model and later on, Canay (2011) found that Koenker's methodology is computationally intensive; therefore, he introduced a two-step procedure of a fixed effect panel quantile regression model. In the first stage, the conditional mean of u_{it} is estimated and the estimated coefficients are to be calculated to obtain individual fixed effects. In the second stage, estimated individual fixed effects would be deducted from the original dependent variable and finally, standard estimation of quantile regression is used. Our empirical analysis is carried out using the above methodology of Canay (2011). Further, some of the previous studies have applied quantile regression to panel data in their analysis (Apergis et al. 2018; Gozgor et al. 2018; Zhu et al. 2018).

Empirical results and analysis

Preliminary results

The annual average growth rate (in percent) of selected variables for individual countries is presented in Table 1. The highest growth rate of output is experienced in China (9.634) followed by India (6.593), while the lowest growth rate is experienced by Russia (0.690). Similarly, the annual growth rate of CO_2 emissions is higher in the case of India (5.332) and China (5.331) and lowest and negative in Russia (− 1.552). Among the BRICS countries, the growth rate of hydropower energy consumption is highest in South Africa (32.032) and China (9.217) followed by India (3.127) and lowest in Russia (0.719). Further, South Africa and India have positive and highest average growth rate of the population, whereas the growth rate of Russia (− 0.085) is negative during the sample period 1990–2016. In general, it is observed from

Table 1 Annual average growth rate, 1990–2016 (percent)

Variable	Brazil	Russia	India	China	South Africa
GDP	2.296	0.690	6.593	9.634	2.377
HYD	2.468	0.719	3.127	9.217	32.032
POP	1.295	− 0.085	1.645	0.777	1.648
CO_2	3.104	− 1.552	5.332	5.331	1.434

The growth rate was calculated using original data

Table 1 that the highest average growth rate of output and CO_2 emissions are occupied by China and India. However, hydropower energy consumption and the population are highest in the case of South Africa. Further, the annual average growth rate of all the considered variables is lowest and negative in Russia.

The mean statistics of individual countries of the BRICS are reported in Table 2. The highest per capita output belongs to China (28.732) and Brazil (28.167) followed by Russia (27.835), India (27.638), and South Africa (26.428). It suggests that there is a consistent development of per capita output across the sample countries. The per capita hydropower energy consumption is higher in China (4.368) and Brazil (4.252) than Russia (3.648) and India (3.031), whereas hydropower energy consumption is lowest and negative in South Africa (− 1.351). The average per capita CO_2 emissions in China (8.485) and Russia (7.382) are higher than those in South Africa (5.921) and Brazil (5.775). The population is highest in China (20.965) and India (20.814) in comparison with Russia (18.795) and South Africa (17.648) during the sample study period.

We also presented the summary statistics of panel dataset in Table 3. The results show that the average economic output across the sample countries is 27.76%. It implies that selected countries have a significant economic outcome during the study period. The average population is about 19.44%, while CO_2 emissions are 6.92%. Finally, hydropower energy consumption accounts for 2.78%. It suggests hydropower energy use remains relatively low, but it is significantly growing in a panel of the BRICS countries.

Table 2 Mean statistics for individual countries, 1990–2016

Country	GDP	HYD	POP	CO_2
Brazil	28.167	4.252	19.008	5.775
Russia	27.835	3.648	18.795	7.382
India	27.638	3.031	20.814	7.039
China	28.732	4.368	20.965	8.485
South Africa	26.428	−1.351	17.648	5.921

HYD per capita hydropower energy consumption in million tons oil equivalent, *GDP* per capita real GDP in constant 2010 US$; CO_2 per capita carbon dioxide emissions in million tons oil equivalent, *POP* total population

Results of cross-sectional dependence tests

Before applying any econometric techniques which deal with panel data analysis, one should always check whether there is a presence of cross-sectional dependence or independence among the variables. The results of conventional unit root tests are spurious and misleading if the variables are found to be cross-sectional dependence because it is based on the assumption of cross-sectional independence. Hence, we employed the cross-sectional dependence (CD) test propounded by Pesaran (2004) in order to investigate the presence of cross-sectional dependence and heterogeneity problem associated in our study. The CD test results are shown in Table 4. The results reveal that the null hypothesis of cross-sectional independence is significantly rejected against the alternative hypothesis of cross-sectional dependence at the 1% level of significance. It suggests that there is a presence of cross-sectional dependence among all of the variables.

Results of panel unit root tests

Since conventional unit root tests are not suitable in the presence of cross-sectional dependence across the sample, we have utilized Pesaran's (2007) CADF and CIPS cross-sectional augmented panel unit root tests which account for cross-sectional dependence. The CADF and CIPS tests results are reported in Table 5. The results indicate that the data series is stationary at the level for population and CO_2 emissions variables which follows I (0), while other variables, namely, economic growth and hydropower energy consumption, are stationary at the first difference which follows I (1). However, all of these variables reject the null hypothesis of non-stationary at the first difference. Based on these findings, we conclude that the considered variables have different orders of integration, i.e., I (0) and I (1). Therefore, we applied the panel ARDL model to examine the short-run and long-run relationship among hydropower energy consumption, economic growth, and population and CO_2 emissions in the BRICS countries.

Results of panel ARDL model

To examine the short-run and long-run relationship among the variables, we have employed the panel ARDL model. This

Table 3 Panel summary statistics

Variable	Mean	Std. dev.	Minimum	Maximum
GDP	27.760	0.885	26.098	29.882
HYD	2.789	2.177	− 3.410	5.572
POP	19.446	1.275	17.420	21.044
CO_2	6.921	1.051	5.284	9.129

Table 4 Cross-sectional dependence test results

Variable	GDP	HYD	POP	CO_2
Pesaran CD test	14.73***	6.68***	3.89***	5.46***
P value	0.000	0.000	0.000	0.000

***Indicates the rejection of null hypothesis of cross-sectional independence (CD test) at the 1% significance level

test can provide more robust and reliable results even in the presence of different orders of integration in the model. The results of long-run and short-run estimates based on panel ARDL model are reported in Table 6. When economic growth is a dependent variable, the results of long-run estimates show that hydropower energy consumption, CO_2 emissions, and population are positively associated with economic growth. It implies that a 1% increase in hydropower energy consumption, CO_2 emissions, and population increases economic growth by 0.038%, 0.349%, and 0.834%, respectively. Our results are consistent with those of Ziramba (2013) in Egypt and South Africa and Solarin and Ozturk (2015) in seven Latin American countries. The ECM coefficient is negative (− 0.629) but not significant. Moreover, in the short run, the results also revealed that hydropower energy consumption promotes economic growth. More technically, a 1% increase in hydropower energy consumption increases economic growth by 0.098% and 0.048% in the lagged periods.

When CO_2 emission is a dependent variable, economic growth increases CO_2 emissions while hydropower energy consumption and population reduce CO_2 emissions. It indicates that a 1% rise in economic growth increases CO_2 emissions by 0.282%, while a 1% increase in hydropower energy consumption and population decreases CO_2 emissions by − 0.227% and − 1.375, respectively. This suggests that high economic growth plays a very significant role in promoting CO_2 emissions which may be due to rapid industrialization

Table 5 Panel unit root test results

Variable	CADF		CIPS	
	Ztbar	*P* value	Ztbar	*P* value
GDP	− 0.968	0.166	3.126	0.999
HYD	0.779	0.782	− 0.619	0.267
POP	− 5.982***	0.000	− 6.905***	0.000
CO_2	− 1.396*	0.081	0.813	0.791
ΔGDP	− 1.998**	0.023	− 2.939***	0.001
ΔHYD	− 7.111***	0.000	− 6.518***	0.000
ΔPOP	− 1.821**	0.034	0.729	0.767
$ΔCO_2$	− 3.745***	0.000	− 4.230***	0.000

Δ is the first difference term. *, **, and ***indicate the rejection of null hypothesis of unit root at the 10%, 5%, and 1% significance levels, respectively

Table 6 Panel ARDL estimation results

$GDP = f(HYD, CO_2, POP)$			$CO_2 = f(HYD, GDP, POP)$		
Variable	Coefficient	Prob.	Variable	Coefficient	Prob.
Long-run equation			Long-run equation		
HYD	0.038**	0.021	HYD	− 0.227*	0.076
CO_2	0.349***	0.000	GDP	0.282**	0.020
POP	0.834***	0.000	POP	− 1.375**	0.037
Short-run equation			Short-run equation		
COINTEQ01	− 0.629	0.409	COINTEQ01	− 0.452***	0.000
D(GDP(− 1))	0.261	0.549	D(CO_2(− 1))	− 0.129	0.522
D(GDP(− 2))	− 0.012	0.953	D(CO_2(− 2))	− 0.101	0.625
D(GDP(− 3))	0.300**	0.014	D(CO_2(− 3))	− 0.172	0.327
D(HYD)	0.040	0.585	D(HYD)	− 0.063	0.405
D(HYD(− 1))	0.083	0.333	D(HYD(− 1))	− 0.031	0.739
D(HYD(− 2))	0.098**	0.011	D(HYD(− 2))	− 0.004	0.938
D(HYD(− 3))	0.048*	0.084	D(HYD(− 3))	− 0.010	0.742
D(CO_2)	0.031	0.949	D(GDP)	0.381	0.225
D(CO_2(− 1))	− 0.025	0.944	D(GDP(− 1))	0.034	0.856
D(CO_2(− 2))	0.152	0.260	D(GDP(− 2))	0.213	0.139
D(CO_2(− 3))	0.030	0.854	D(GDP(− 3))	0.158	0.422
D(POP)	− 175.520	0.244	D(POP)	− 181.966	0.154
D(POP(− 1))	306.328	0.252	D(POP(− 1))	379.017	0.152
D(POP(− 2))	− 228.693	0.233	D(POP(− 2))	− 233.877	0.312
D(POP(− 3))	38.855	0.230	D(POP(− 3))	− 7.741	0.937
Constant	5.630	0.429	Constant	12.605***	0.000

*, **, and ***indicate the rejection of null hypothesis of unit root at the 10%, 5%, and 1% significance levels, respectively. The lag length is chosen based on AIC

and urbanization in recent periods, while hydropower energy consumption helps to mitigate CO_2 emissions in the BRICS countries. Our results are similar with those of Solarin et al. (2017) in India and China, and contradict those of Ummalla and Samal (2018) in China. The ECM coefficient is negative (− 0.452) and statistically significant at the 1% level. In the short run, we have observed that hydropower energy consumption and population have a negative impact on CO_2 emissions, while economic growth has a positive impact on it at the insignificant level.

In sum, regarding the panel ARDL test results on all the considerable variables, we can highlight that hydropower energy consumption, CO_2 emissions, and population are considered the significant drivers in order to achieve higher economic growth in the BRICS countries. The economic growth and population raise CO_2 emissions, while hydropower energy use reduces it. Therefore, governments and policymakers should take appropriate policy initiatives, namely, shifting tax incentives and invest fund on hydropower energy projects through foreign direct investment and foreign institutional investment in order to promote hydropower energy use rather than non-renewable energy sources. The increase in investment in hydropower energy projects increases the energy generation capacity and meets the demand for hydropower energy consumptions to mitigate CO_2 emissions without compromising in achieving higher economic growth in the BRICS countries.

Results of panel quantile regression (PQR) estimates

The results of panel quantile regression (PQR) estimates are reported in the upper panel of Table 7 when economic growth is considered a dependent variable. The results of 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th, and 95th percentiles are represented in conditional growth distributions. The impact of hydropower energy consumption on economic growth is heterogeneous across quantiles. The marginal impact of hydropower energy consumption on economic growth is higher at the higher quantile levels. The hydropower energy consumption significantly promotes economic growth at the 1% level of significance across the quantiles (except the 10th quantile level). It demonstrates that a 1% rise in hydropower energy consumption promotes economic growth by 0.214–0.319%. More technically, whether in low-income countries or high-income countries, based on these findings, we urge that hydropower energy consumption is a primary source of energy for enhancing economic growth in the BRICS countries over the period.

Next, regarding the CO_2 emission variable, we can see that there is a presence of the heterogeneous impact of CO_2 emissions on economic growth across the quantile in the conditional distribution of economic growth. The impact of CO_2 emissions on economic growth is positive and insignificant at the first three quantile levels, namely, 10th, 20th, and 30th, while the coefficients are positive and significant at the higher quantile levels (60th–95th quantiles) which indicates that the influence of CO_2 emissions on economic growth is positive. It implies that a 1% increase in CO_2 emissions promotes economic growth by 0.336–0.473% in high-income countries. The marginal impact of CO_2 emissions on economic growth is higher at the higher quantiles of income. From these results, we can see that the high-income countries are more reliant on fossil fuels, in turn to high CO_2 emissions which has a severe impact on climate change, to achieve their high growth targets. However, we can suggest that high-income countries should mitigate CO_2 emissions by consuming renewable energy sources without compromising economic growth. In other words, high-income countries should invest more funds on the development of energy infrastructure, setting of new less-energy intensive industries, and spending on research and development (R&D) which can combat CO_2 emissions and also boost economic growth. Regarding population variable, the impact of population on economic growth is different across quantiles. The coefficients of population are negative and insignificant in most of the quantiles. However, it is negative and significant in higher quantiles, namely, 90th and 95th quantiles. These findings imply that an increase in the population reduces the economic growth. It suggests that the population retards economic growth in the BRICS countries.

The results of panel quantile regression (PQR) estimates are represented in the lower panel of Table 7 when CO_2 emissions are considered a dependent variable. We also observe that the influence of hydropower energy consumption on CO_2 emissions is heterogeneous in the conditional distribution of CO_2 emissions. The impact of hydropower energy consumption on CO_2 emissions is negative and significant at the 5% level at the lower quantile levels (i.e., 10th, 20th, 30th, and 40th quartiles). These empirical findings demonstrate that hydropower energy consumption plays a significant role in mitigating CO_2 emissions in lower CO_2 emissions countries. However, coefficients became insignificant in 50th and 60th quantiles. Further, the coefficients of hydropower energy consumption are positive and significant on CO_2 emissions in higher quantiles (i.e., 80th, 90th, and 95th quantiles). It suggests that hydropower energy consumption promotes CO_2 emissions in higher CO_2 emission countries. In other words, these countries are heavily consuming non-renewable energy rather than renewable energy for their economic activities. Therefore, the use of hydropower energy does not help mitigate CO_2 emissions in high-CO_2 emission countries. Further, coefficients of economic growth are positive and significant at the 1% levels on CO_2 emissions across the quantiles. These results suggest that whether in low-CO_2 emission or high-CO_2 emission countries, economic growth has significantly increase emissions. Moreover, the findings also revealed that coefficients of the population are significant and positive at the 1% level across the quantiles. From these results, we can report that the population has significantly enhanced emissions in the BRICS countries.

Conclusion and policy implications

In the recent period, there is a concern on global warming and climate change among the policymakers and environmental scientists, which are mainly caused by combustion of conventional energy sources for achieving the high economic growth target, rapid industrialization, and rising population. Therefore, many international organizations and individual countries in the world have taken it as the early warning system and started promoting renewable energy sources in order to mitigate CO_2 emissions in a side and meet the demand for energy on another side. Given the above background, in this paper, we aim to explore the effects of hydropower energy consumption on economic growth and CO_2 emissions in the BRICS countries, spanning the period 1990–2016. For this

Table 7 Panel quantile regression (PQR) results

Variable	10th	20th	30th	40th	50th	60th	70th	80th	90th	95th
GDP= f (HYD, CO_2, POP)										
Constant	25.773***	27.818***	26.921***	26.694***	25.985***	26.641***	27.200***	27.821***	28.618***	28.236***
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HYD	0.214	0.342***	0.337***	0.344***	0.327***	0.322***	0.339***	0.348***	0.336***	0.319***
	0.225	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000	0.000
CO_2	0.336	0.037	0.101	0.170**	0.180**	0.302***	0.366***	0.425***	0.468***	0.473***
	0.436	0.564	0.102	0.015	0.016	0.006	0.001	0.000	0.000	0.000
POP	− 0.075	− 0.081	− 0.050	− 0.059	− 0.019	− 0.088	− 0.137	− 0.186	− 0.236**	− 0.214**
	0.325	0.108	0.311	0.313	0.069	0.471	0.356	0.167	0.035	0.047
Pseudo *R*-squared	0.599	0.606	0.603	0.591	0.578	0.573	0.590	0.627	0.702	0.737
Adjusted *R*-squared	0.590	0.597	0.594	0.582	0.966	0.563	0.580	0.618	0.695	0.731
CO_2 = f (HYD, GDP, POP)										
Constant	− 31.298***	− 29.334***	− 28.878***	− 28.029***	− 22.446***	− 20.837***	− 16.658***	− 13.063***	− 11.514***	− 11.871***
	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.0000	0.000	0.000
HYD	− 0.402***	− 0.416***	− 0.407***	− 0.396***	− 0.085	− 0.053	0.012	0.079**	0.114***	0.099***
	0.0000	0.000	0.000	0.000	0.219	0.420	0.802	0.034	0.000	0.000
GDP	0.922***	0.864***	0.854***	0.846***	0.975***	0.870***	0.695***	0.556***	0.540***	0.567***
	0.000	0.000	0.002	0.006	0.000	0.000	0.000	0.000	0.000	0.000
POP	0.671***	0.659***	0.650***	0.619***	0.140**	0.209**	0.242**	0.251***	0.192***	0.177***
	0.000	0.000	0.000	0.000	0.053	0.017	0.012	0.005	0.009	0.004
Pseudo *R*-squared	0.462	0.455	0.442	0.422	0.450	0.469	0.516	0.584	0.657	0.672
Adjusted *R*-squared	0.449	0.443	0.429	0.409	0.437	0.456	0.505	0.575	0.649	0.665

** and ***Imply the significance levels at the 5% and 1%, respectively

purpose, we have applied several panel econometric methodological approaches.

The empirical findings based on the panel ARDL model manifest that in the long run, hydropower energy consumption, CO_2 emissions, and population promote economic growth. However, hydropower energy consumption and population reduce CO_2 emissions, while economic growth positively contributes to CO_2 emissions. These results are similar to the findings of Solarin et al. (2017) in China and India. However, it contrasts with findings of Ummalla and Samal (2018) in China. In the short run, hydropower energy consumption has a positive association with economic growth, while hydropower energy consumption and population have a negative association with CO_2 emissions, and economic growth has a positive impact on it at the insignificant level. These outcomes are similar with Solarin et al. (2017) in China and India.

Furthermore, our panel quantile regression results indicate that the effects of independent variables on economic growth and CO_2 emissions are heterogeneous across the quantiles. When economic growth is a dependent variable, the marginal impact of hydropower energy consumption on economic growth is positive and significant at the 1% level at all the quantile levels (except the 10th quantile). It implies that hydropower energy consumption has a substantial positive impact on economic growth in low- and high-income countries. Next, CO_2 emissions have a positive and significant impact on economic growth at the low and high quantile levels (i.e., 40th–95th quantile). Finally, an increase in the population reduces the economic growth at higher quantiles (namely, 90th and 95th quantiles) in BRICS countries.

When CO_2 emission is a dependent variable, hydropower energy consumption plays a significant role in mitigating CO_2 emissions in lower CO_2 emission countries (i.e., 10th, 20th, 30th, and 40th quantiles). However, hydropower energy consumption promotes CO_2 emissions at the higher quantile levels (i.e., 80th, 90th, and 95th quantiles) in higher CO_2 emission countries. Further, coefficients of economic growth are positive and significant on CO_2 emissions across the quantiles. Besides, the findings also revealed that higher population enhances the CO_2 emissions across quantiles in the BRICS countries. Based on the empirical findings, we observed that hydropower energy consumption positively affects the economic growth and it shows that hydropower energy is the driving force of economic growth. Similarly, use of the hydropower energy negatively affects CO_2 emissions which postulates that hydropower energy is the potential determinant of mitigating CO_2 emissions. Therefore, the benefits of this type of energy consumption help to cut down CO_2 emissions in line with the goal of sustainable economic growth. Hence, our findings of the paper imply that policymakers of the BRICS countries should reduce CO_2 emissions by using hydropower energy without reliance on fossil fuels in order to meet their energy demands and sustainable economic growth.

Based on the above findings, we highlight the following important policy implications. (1) The hydropower energy consumption is considered an essential driver to achieve rapid economic growth, and it also helps in mitigating CO_2 emissions in the BRICS countries. Therefore, governments and policymakers should frame appropriate policies in favor of the deployment of hydropower energy projects. (2) Any conservation hydropower energy policies will have a negative impact on economic growth. Therefore, expansionary of hydropower energy policies is useful for the BRICS countries. (3) Since expansionary hydropower energy policies are beneficial to the countries, it should be considered a feasible policy and also substituting it for fossil fuel to mitigate CO_2 emissions (Solarin and Ozturk 2015). (4) Policy makers should also promote hydropower energy generation and consumption by introducing appropriate incentives, e.g., tax rebates and subsidies (Apergis et al. 2016). (5) Financing in hydropower energy projects through the stock market developments, foreign direct investment (FDI), and official development assistance (ODA) will promote hydropower energy generation which is a solution for addressing global warming and climate change. (6) Governments of the BRICS countries should encourage public-private partnership investments in hydropower energy projects. (7) These economies should also introduce investment subsidies and tax incentives to attract investors in energy projects to ensure energy security and stability. (8) As suggested by the Paris Summit, developed countries should do financial support to developing countries, and BRICS development bank also increases more funds and allocates among the BRICS countries for adaption of innovations and technologies in hydropower energy generation and mitigation of CO_2 emissions. Finally, since hydropower energy use has a positive impact on economic growth and negative impact on CO_2 emissions, the BRICS countries should follow the expansionary hydropower policies for better sustainable economies in the world.

The present study is conducted on the BRICS countries. However, in light of awakening global awareness towards mitigating CO_2 emissions and sustainable economic growth, future studies should be conducted on developed and developing countries to capture the larger impact of hydropower energy consumption. Furthermore, researchers can examine the impact of hydropower energy consumption on economic growth and CO_2 emissions in these countries by incorporating other variables like institutional quality, R&D, and financial development in the model.

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