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Research article

Analyzing the nexus between energy transition, environment and ICT: A step towards COP26 targets

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ABSTRACT

In line with the Sustainable Development Goals and the recent COP26 summit, energy transition, low carbon emissions and technology have become extremely important subjects in the agenda of governments and policymakers. The present study thus discusses the nexus between energy transition, economic growth, CO_2 emissions and information and communications technology (ICT) in BRICS countries applying the novel GMM-PVAR method proposed on the annual data for the period 2000–2017. This method is strong to the issue of endogeneity which is commonly faced in the context of panel data analysis but mostly ignored in the literature. The findings of this research demonstrate that carbon emissions have a positive and significant effect on energy transition; similarly, raising economic growth augments the consumption of energy transition. Furthermore, ICT is found to be a significant choice in the development of energy transition and the solution of environmental challenges. Overall, technological factors in addition to economic and environmental factors also have great roles in the development of renewable energy and energy transition. Thus, results from this study call for government supports to develop ICT across the BRICS countries.

1. Introduction

In recent years, one of the main problems that societies have faced is the emission of pollutants and environmental degradation (Olanrewaju et al., 2019; Sequeira and Santos, 2018; Toumi and Toumi, 2019; Tsiantikoudis et al., 2019). Based on the United Nations Climate Change Conference (COP26) held in Glasgow in 2021, countries around the world have to confront environmental issues. Accordingly, world leaders pledged to reduce greenhouse gas emissions and limit world temperatures to 1.5 °C by 2050 (Goals, 2021; Fahimi et al., 2018; Balibar, 2017). Eliminating fossil fuels in energy production is one of the best paths to minimize pollutant emissions and global warming. Renewable energy use is a good alternative to fossil fuels (Lu, 2018; Shao et al., 2021). In the report of the International Energy Agency has stated that the world's renewable energy will increase by 50% for period 2019–2024 (IRENA (International Renewable Energy Agency), 2020). In another report, the International Renewable Energy Agency forecasts that two-thirds of the world's energy will be sourced from renewable energy by 2050 (Kais and Mounir, 2017). Unlike non-renewable energy, renewable energy sources are sustainable and do not emit much carbon dioxide (Mohsin et al., 2021). Therefore, renewable energy development has become a key factor in moving to a low-carbon economy (Raheem et al., 2020). The development of renewable energy by decreasing carbon dioxide emissions can diminish the Impacts of climate change and help advance sustainable development goals such as energy security and lowering environmental impacts (Belaïd and Zrelli, 2019; Streimikiene et al., 2021). However, due to structural problems such as financial constraints, it is unlikely that renewable energy transition does without government interposition (Dumitrescu and Hurlin, 2012). Government protection policies such as environmental tax revenues can also motivate the use of renewable energy (Abban and Hasan, 2021). Thus, due to the importance of renewable energy deployment, there is a fundamental need to investigate the determinants of energy transition.

A green economy is recognized by the use of low-carbon resources and renewable energy (Godil et al., 2020). The transition to a low-carbon economy requires significant changes at different levels of economics, companies and governments must also turn to technological innovations to achieve their zero-emission targets (Mukhtarov et al.,

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2022a). The International Telecommunication Union reports that ICT is a key factor in reinforcing innovation to achieve SDG goals across countries (International Telecommunication Union (ITU), 2020; Jacqmin, 2018). The World Energy Council has stated that the development of the ICT will enhance energy efficiency via better management of energy resources (Zhao et al., 2013). In fact, information and communication technology can increase the share of renewable energy in the total level of energy consumption and promote energy efficiency (Nguyen and Kakinaka, 2019). Over the past two decades, emerging economies have seen considerable growth in information and communications technology (ICT) (International Energy Outlook, 2019). The expansion of the ICT sector can be crucial in maximizing the production of renewable resources. Information and communication technology can also be used to comfort the storage of electricity generated from renewable sources (Ahmed et al., 2017).

BRICS is the name of a group led by emerging economic powers (Brazil, India, Russia, South Africa, and China). The BRICS countries account for 45% of world agricultural output, 34% of PPP adjusted global GDP, 42% of the world population, 24% of the global GDP, 17% of the world trade, 13% of the global service market, and engrossing 38% of world energy. Thus, these countries account for a significant share of global CO_2 emissions (Holtz-Eakin et al., 1988; World Energy Council, 2018). Based on the (BP, 2021), China has the highest CO_2 emissions in among the BRICS countries and world. In 2020, China's total CO2 emissions accounted for 28.8% of total global emissions. India has 7.3% of total global emissions and is ranked third in the world. Russia, South Africa and Brazil emit 4.5%, 1.4% and 1.3% of carbon dioxide, respectively. The BRICS account for 43.3% of the world's total carbon emissions in 2020. According to (BP, 2021), the BRICS countries account for 36.4% of the world's total renewable energy generation.

There is an extensive literature that surveyed the effect of CO_2 emissions on renewable energy. Some researchers have shown that high levels of carbon emissions help enhancement renewable energy development (Chen et al., 2021; Lutkepohl, 2005). But another group believes that CO_2 emissions do not have an important role in the use of renewable energy (Gibson et al., 2017; Miller, 2020; Mukhtarov et al., 2020). Furthermore (Polcyn et al., 2022), and (Belaïd et al., 2021) concluded that CO_2 emissions do not play a significant role in the support of renewable development. On the other side, another driver of sustainable development and renewable energy deployment is the achievement of economic growth (IEA, 2020; Tudor and Sova, 2021). In addition (Bamati and Raoofi, 2020), noted that higher economic growth (GDP) can cover the costs of renewable energy generation, because the costs of renewable energy technologies are generally more than fossil fuels. In fact, high-income countries can easily pay for the development of renewable technologies and move to energy transition faster than low-income countries (Bersalli et al., 2020; Chang et al., 2009; Raheem et al., 2020; Samour et al., 2022). Therefore, the deployment of renewable energy/energy transition, due to high costs and long delays in gaining economic benefits, is in dire need of government support (Westerlund, 2007; Shao et al., 2021). So that the International Energy Agency considers government support for renewable energy projects to be an important factor (Ibrahiem and Hanafy, 2021). Indeed, the environment and renewable energy are more important in democratic societies than in authoritarian regimes (Sigmund and Ferstl, 2021).

In lights of the above-mentioned explanations and arguments, this study for the first time aims to evaluate the nexus of energy transition, economic growth, carbon emissions and ICT by applying the econometric method GMM-PVAR of Sigmund and Ferstl (2021) (Simionescu et al., 2020) on the data for the period 2000–2017 for BRICS countries. Furthermore, only a few studies have considered the role of ICT in the context of energy transition. Besides, this is the first research that applies the extended Panel Vector Autoregression model (GMM-PVAR) on the subject of the determinants of energy transition. In view of likely endogeneity issue in the estimated models, this attempt is very supportive to obtain more valid and robust outcomes. The remaining part of this study is organized as follows. Section 2 will present literature review. Section 3 investigates the data and econometrics methods; Section 4 demonstrates empirical analyses while Section 6 presents the discussion. Finally, the conclusion and policy implications are given in Section 6.

2. Theoretical background and literature review

2.1. The literature on ICT overview

Few researches have recognized the motivation of Information and Communication Technologies (ICT) on renewable energy. For instance (Nathaniel et al., 2021), analyzed effect of ICT-trade on renewable energy in South Asian. The finding of research showed that ICT trade enhances renewables consumption, and increases renewable energy shares (Tan and Uprasen, 2021). examined the impact of mobile information communication technologies on the development of renewable energy in two North American countries and five European countries from 2000 to 2018. According to static and dynamic empirical analyses, ICTs promote the renewable energy in long/short run. By applying GMM, ordinary least-squares, fixed effect and random effect models (Chowdhury et al., 2021), observed positive and significant impact of ICT on renewables consumptions in India and China during 1991–2020.

On the other, some papers have examined the effect of ICT on CO_2 emissions. For example (Lin et al., 2016), found that the ICT stimulates CO_2 emissions in emerging countries during 1990–2015. By using Pooled Mean Group (Sadorsky, 2009), concluded that ICT increases carbon emissions in long-run in the G7 countries during 1990–2014 (Batool et al., 2022). indicated that ICT positively contributes to CO2 emission in the long-term in East and South Asia countries from 1985 to 2020. Also, the Granger Causality test showed a causality from ICT to carbon emissions. Some studies also show that ICT helps reduce the consumption of energy and carbon dioxide emissions (Marinaș et al., 2018). investigated the impacts of ICT on carbon emissions in Asian countries. The results displayed that the impact of ICT on CO2 emissions is significantly and negative. Using quantile autoregressive distributed lag method (Gozgor et al., 2020), showed that ICT decreases CO2 emissions in Pakistan from 1995Q1-2018Q4. Whit applying CUP-FM long-run method (Ahmed and Le, 2021), reveals ICT contributes to mitigating CO2 emissions in ASEAN countries (Murshed, 2020b). showed the non-parametric stream of ICT on renewable energy transition and environmental sustainability in South Asia. In the same vein (Murshed et al., 2020b), verified the influence of ICT on renewable energy transition and environmental sustainability employing a sample of six Asian countries. The key role of ICT and renewable energy on energy transition have been present by using a distribution network model (Nijhuis et al., 2015).

2.2. The literature on CO_2 emissions, economic growth and renewable energy

The literature on the relationship between CO_2 emission and renewable energy development has not reached any consensus yet. Several researchers have concluded that increasing CO_2 emissions increases the renewable development. For example (Pedroni, 2004), studied the factors affecting on renewable energy in 64 countries during 1990–2011 by using a GMM panel method. Their findings indicated that CO_2 emissions rise the use of renewable energy. A study on 30 provinces of China by (Chen, 2018) was conducted in the period from 1996 to 2013 aimed to investigates the factors influencing renewable energy. The dynamic GMM panel method was used to analyze the data. The finding of this study proposes that carbon emissions have a positive impact on renewables consumption. Whit applying the random-effects and the panel FMOLS estimations (Gusarova, 2019), demonstrated that the effect of carbon emissions on renewables is positive in OECD countries from 1970 to 2015 (Bamati and Raoofi, 2020). examined the drivers of renewable energy production for developed and developing economies by using GLS method. The research results showed carbon emissions drive the renewable energy production in developing countries. By applying panel ARDL method (Wang et al., 2020), concluded that CO2 emissions have had a positive impact on renewable consumption in 43 countries for over period 2000–2015 (Wang, 2019). found that CO_2 emission increase renewable energy consumption 38 countries during 1990–2015. ARDL-PMG method was used for data analysis (Raheem et al., 2020). examined factors influencing the renewable consumption for European countries employing a fixed-effects regression and GMM for annual data from 2000 to 2018. The results illustrated the positive relationship between renewable consumption and CO_2 emissions.

Some researchers have concluded that CO_2 emissions did not analyzed the development of renewable energy. For an instant, by applying panel ARDL model (da Silva et al., 2018), studied the determinants of renewables in sub-Saharan African countries for 1990–2014. In this paper, it was concluded that carbon emissions negatively affected renewable energy development (Papież et al., 2018). researched the relationship between renewable energy and carbon emission in African countries for 1990–2015 by panel fixed effects model. The outcomes displayed that the impact of carbon emission on renewable consumption is negative (Ritchie and Roser, 2020). analyzed factors influencing renewable energy generation in 27 transition countries from 1990 to 2014. They found that increasing CO_2 emissions significantly limited energy renewable production (Bayale et al., 2021). using Bayesian Model Averaging, FMOLS and DOLS methods have shown that CO_2 emissions interdict generation of renewable energy in WAEMU countries. Using General to Specific modeling method (Murshed, 2020a), investigated the effect of oil price on the renewable energy consumption for Iran for 1980 to 2019. The findings displayed that oil price and CO_2 emissions reduce renewable consumption.

In some researches, the importance of output was confirmed for the development of renewable energy. For example, a research on China was conducted by (Lu, 2017). They investigated the determinants affecting the consumption of renewable electricity using a johansen cointegration and vector error correction method from 1980 to 2011. The findings showed that GDP increases the renewables share in consumption of electricity. Using dynamic panel data methods (Ben Mbarek et al., 2018), displayed a one-way causality from GDP to renewable consumption in the long and short-term for developed and developing 18 countries over 1990–2013 (Zheng and Wang, 2021). demonstrated GDP is an increasing factor for renewable energy deployment for OECD economies from 1965 to 2014. With utilizing structural time series modeling approach (Mukhtarov et al., 2022b), revealed that there is a positive effect of economic growth on renewable energy from 1992 to 2015 in Azerbaijan (Liu et al., 2021). indicated that GDP drives the consumption of renewable energy in OECD during the period 1990–2017. In this paper, the model is estimated with the cross-sectional Autoregressive Distributive Lag method (Sweidan, 2021). researched the relation between GDP and renewable sources in the European Union countries for period 2007–2017. The results showed a causality from GDP to renewable energy (Li et al., 2020). surveyed the relation between GDP, oil price, carbon emissions and renewable energy consumption in Russia by utilizing the Vector Error Correction method and the Canonical Cointegrating Regression model from 1990 to 2015. The result of study indicated the negative effect oil price on the use of renewable energy, while influence of GDP was positive and significant on the consumption of renewable. In doing so, CS-ARDL method has applied. Whit applying CS-ARDL method, Su et al. (2021) indicated that increasing GDP rise the use of renewable energy in long-run and short-run for 7 OECD countries over 1990–2018 (Murshed et al., 2020a). evaluated the effect of GDP, financial development, and energy prices on consumption of renewable energy by VECM and ARDL techniques the period from 1980 to 2019 for Turkey. The results indicated that GDP has the impact of positive on renewable energy. By using the new technique of bootstrap autoregressive distributed lag (Shahbaz et al., 2022), reveals economic growth can raise the consumption of renewables in the UAE from 1989 to 2019. Based on the Renewable Energy Country Attractiveness Index (Simionescu et al., 2019), concluded that economic growth increases renewable energy consumption for 39 countries over during 2000–2019.

As shown in the two subsections above, researchers have used various first-generation econometric methods to model the factors affecting the energy transition, mainly in high-income countries. But the present paper relies on modern estimation approaches. Unlike previous studies and to the best of the authors knowledge, it can be acknowledged that the current study is the first paper that investigates the impact of CO_2 emissions, economic growth, and ICT on renewable energy in BRICS countries through the extended Panel Vector Autoregression model (GMM-PVAR).

3. Model, data and methodology

3.1. Model, theoretical background and data

In the light of the above-mentioned theoretical and empirical review, especially, in view of (Bourcet, 2020) and (Dong et al., 2017), this research focuses on the following model:

$$RE_{it} = f(GDP_{it}, CO_{2it}, ICT_{t},) \tag{1}$$

We use the largest available annual data of BRICS countries (Brazil, Russia, India, China and South Africa) during period from 2000 to 2017 in order to explore the relationship among energy transition/renewable energy (RE), carbon dioxide emissions (CO_2), economic growth (real GDP) and information and communication technology (ICT). The share of RE is collected from OurWorldInData (Salehnia et al., 2020), GDP dataset are in millions of 2017 USD and were gathered from the Penn World Table version 10.0 (https://www.rug.nl/ggdc/productivity/pwt/?lang=en) following (Geng and Ji, 2016), CO_2 variable is in million tonnes (BP, 2021) whilst ICT dataset are in U.S. dollars and were sourced from the World Development Indicators (http://data.worldbank.org/). The descriptive statistics of the data are shown in Table 1. For instance, ICT has the largest mean, and the lowest mean among the variables belongs to RE. Also, RE and GDP have the lowest and highest median, respectively.

3.2. Methodology

Sigmund and Ferstl (2021) (Simionescu et al., 2020), proposed a new extension of general methods of moment panel vector autoregression model (GMM-PVAR). Initially, based on vector autoregressive panel model of (Hussain et al., 2022), (Simionescu et al., 2020) suggested a PVAR model with fixed effects allowing numerous θ lags of m endogenous variables with k weakly exogenous-predetermined and h strictly exogenous variables. The computational definition of this model is as follows:

$$s_{i,t} = y_i + \sum_{e=1}^{\theta} W_n s_{i,t-e} + N f_{i,t} + \Phi d_{i,t} + z_{i,t} \tag{2}$$

Endogenous variables are shown from the letter $s_{i,t-1}$ while the weakly and strictly exogenous variables are depicted by the letters $f_{i,t}$ and $d_{i,t}$, respectively. Moreover, the first difference or the forward

Table 1
Descriptive statistics table.

Variables	Max	Min	Mean	Median	Std.dev
RE	44.94	0.26	12.18	6.13	14.7
GDP	19,687.16	454.86	4790.90	3166.83	4663.96
ICT	78,518.52	35.03	11,743.22	1772.17	21,085.29
CO_2	9466.36	306.37	2208.85	1458.26	2705.56

orthogonal transformation models can be applied instead of fixed effects for more robust finding. In addition to, the GMM procedure can be used applying the coefficients as instrumentals covariates. Apart from that, an extension of the estimator of (Binder et al., 2005) is utilized by (Simionescu et al., 2020) rising the lags of the endogenous, weakly and strictly exogenous covariates. The computational definition of this model is as follows:

$$\Delta s_{i,t} = \sum_{e=1}^{\theta} W_n \Delta s_{i,t-e} + N\Delta f_{i,t} + \Phi\Delta d_{i,t} + \Delta z_{i,t} \tag{3}$$

where the first difference or the forward orthogonal transformation are presented from the letter Δ, $s_{i,t}$ is the lagged endogenous variables, which are RE, GDP, ICT and CO_2, while $f_{i,t}$ and $d_{i,t}$ depict the weakly and strictly exogenous variables, respectively. The stationarity of the framework can be checked employing the stability test. If all the eigenvalues lie inside the unit circle (values of each variable <1), then PVAR verifies stability condition. Finally, (Andrews and Lu, 2001)'s lag selection criteria is used for the optional lags. Precisely, they suggest three alternative criteria based on the moment selection criteria (MMSC): the MMSC-AIC (Akaike information criterion), MMSC-BIC (Bayesian information criterion) or the MMSC-HQIC (Hannan-Quinn information criterion). In our model, we implement the MMSC-BIC to choose the lag length (Andrews and Lu, 2001; Simionescu et al., 2020). The outcomes unveil $\theta = 1$.

As a visual depiction, we implement the orthogonal impulse response function (OIRF) method [604]. We used that model in order to examine the response of the one variable to shocks of the other covariates. The estimation of OIRF is as follows:

$$OIRF(b,a) = \frac{\partial z_{i,t+b}}{\partial (q_{i,t})_a} \tag{4}$$

where $z_{i,t}$ exhibits the endogenous covariates (GDP, CO_2 emission, ICT and RE) whilst b show the number of shocks of each period to the $a-th$ component of $q_{i,t}$. Furthermore, for a more robust examination we applied bootstrap confidence bands as proposed by (Kapetanios, 2008; Marques and Fuinhas, 2011). This bootstrap procedure shows the fluctuations of functions for a GMM-VAR model, in our case. In particular, we employ a cross-sectional bootstrap for a panel fashion as constructed by (Khan et al., 2018).

As a further investigation, we apply a Granger non-causality in heterogeneous panel proposed by (Dwivedi et al., 2022). Moreover, this panel Granger causality framework can eliminate the endogenous connection among the variables. The computational procedure for their model can estimated as follows:

$$q_{i,t} = m_i + \sum_{i=1}^{\gamma} \beta_i^{(\gamma)} w_{i,t-b} + \sum_{i=1}^{\gamma} r_i^{(\gamma)} f_{i,t-\gamma} + w_{i,t} \tag{5}$$

where m_i denotes the constant term while $\beta_i^{(\gamma)}$ demonstrates the lag parameter and the coefficient slope are presented $r_i^{(\gamma)}$. According to (Dwivedi et al., 2022) the validity of this method can be estimated by two tests, the Wald statistics (Z_{Wald}) and the estimated moments for limit T datasets (Z_{bar}). Finally, the null hypothesis insinuates that the absence of panel Granger causality for the calculated model whilst the rejection of the null hypothesis shows the existence of panel Granger causality between the variables. Succinctly, the two hypotheses are given as:

$$H_o: \; a_i = 0, \tag{6a}$$

$$H_1: \; a_i = 0, \forall_i = 1, 2, \ldots\ldots\ldots U \tag{6b}$$

$$H_1: \; a_i \neq 0, \forall_i = U_1 + 1, U_1 + 2, \ldots\ldots\ldots U \tag{6c}$$

4. Empirical analysis

4.1. Pre-estimation checks

In Table 2, the correlation among variables in this research are depicted. RE demonstrates a significant and negative correlation with CO2 and ICT. In addition, RE has nothing to possess with GDP. Also, GDP correlation with CO2 and ICT is a significantly positive. The correlation between CO2 and ICT is positive and insignificant. Additionally, the values of VIF verify a multicollinearity problem for CO_2 and GDP variables (also, we can observe it from high value of Pearson's correlation). This outcome is indeed not surprising, likely caused by the potential bidirectional causality (endogeneity) between the variables. Nonetheless, GMM-PVAR can eliminate the issue since it calculates a system of equations containing all the covariates as endogenous. Furthermore, GMM-PVAR by implementing OIRF framework can identify the impact of one exogenous variable (as a shock) to other variables (Sigmund and Ferstl, 2021).

Table 3, panel A asserts the cross-sectional dependence (CD). As shown, CD is visible at the 1% significance level. This finding demonstrates the invalidity of conventional CD tests and is a testament to the use of advanced methods to achieve reliable results. Thus, second-generation unit root tests (CADF and CIPS) are used in this research. According to the results of panel A, all variables are stationary at the first difference (Karacan et al., 2021; Przychodzen and Przychodzen, 2020). and (Yao et al., 2019) tests are used to confirm the long-run cointegration between the variables, as shown in Table 3, panel B. Based on findings, the null hypothesis of "no cointegration" rejects in all three tests. Therefore, it can be said that there is a long-term relation between model variables in the presence of CD.

4.2. Evidence from GMM-PVAR estimation

As described in Section 3-2, the GMM-PVAR method is used to analyze the nexus between energy transition, GDP, carbon emissions and ICT. The results of GMM-PVAR for RE, GDP, CO_2, and ICT are exhibited in Table 4. Since the main focus of this study is to investigate the factors that determine energy transition, so the impacts of these factors on renewable energy are discussed. As Table 4 is indicated, the relations renewable energy (RE) and CO_2 is positive and significant. Such that, a 1% increase in CO_2 has tended to elevate the RE in BRICS economies by 0.20%. This shows that carbon emissions improve the process of transition and development of renewable energy in BRICS economies. In fact, more CO_2 is causing more environmental damage, so more pressure is being put on governments to develop cleaner energy, and as a result, the use of renewable energy is expanded. The same outcome is expressed by (Aguirre and Ibikunle, 2014) for BRICS economies (Omri and Nguyen, 2014), for 107 countries (Gusarova, 2019), for OECD (Tan and Uprasen, 2021), for ASEAN-5. Contrary to our conclusion, some researchers, such as (Ahmadov and van der Borg, 2019) for European Union (Ritchie and Roser, 2020), for 27 countries, confirm the negative relationship between energy transition and CO2 emissions.

GDP also has a positive connection with ER in BRICS economies. The results define that a 1% enhancement in GDP leads to a 0.46% raise in

Table 2
Correlation matrix and VIF statistics.

	RE	GDP	CO_2	ICT
RE	1.00			
GDP	−0.105	1.00		
CO_2	−0.229**	0.963***	1.00	
ICT	−0.189*	0.336***	0.166	1.00
VIF		24.66	22.50	1.83

Notes: ***, **, and * show significance at a 1%, 5% and 10% level, respectively. VIF means variance inflation factors.

Table 3
Tests for panel unit root, cointegration and cross-sectional dependence.

Panel A: Panel unit root tests			
Variables	CD-test	CADF (1st diff.)	CIPS (1st diff.)
lnRE	10.88***	−3.73***	−4.78***
lnGDP	13.01***	−2.31*	−2.87**
$lnCO_2$	11.17***	−3.53***	−4.49***
lnICT	12.10***	−2.86*	−4.50***
Panel B: Panel cointegration tests			
Kao test: 1.31*			
Pedroni test: 4.08***			
Westerlund test: 1.49*			

Notes: ***, **, * show significance at a 1%, 5% and 10% levels, respectively.

Table 4
Results for the GMM-PVAR model.

Dependent variable	$RE_{(t)}$	$GDP_{(t)}$	$CO_{2(t)}$	$ICT_{(t)}$
RE $_{(t-1)}$	1.280***	0.601**	1.045*	0.456
GDP $_{(t-1)}$	0.465	0.815***	0.577	1.406**
CO_2 $_{(t-1)}$	0.201**	−0.725***	0.301***	0.867
ICT $_{(t-1)}$	0.605	2.079**	1.018	−0.099***

Note: ***, **, and * depict significance at a 1%, 5% and 10% level, respectively.

RE. In other words, higher GDP supports regulatory costs to upgrade renewables, as a result, it leads to the deployment of renewable energy/energy transition, thus GDP variable illustrates positive impacts on ER. The result of the present study is consistent with the findings of (Kao, 1999) for European Union (Alam and Murad, 2020), for OECD countries (Uzar, 2020b), for 94 countries (Simionescu et al., 2019), for 39 countries. But studies by (Aguirre and Ibikunle, 2014) and (Pedroni, 2004) show that GDP does not help to promote RE. Finally, GMM-PVAR results indicate a positive effect of ICT on energy transition. So that 1% enhancement in ICT increases RE by 0.60%. Hence, the development of ICT in emerging economies such as BRICS countries, can lead to the promotion of energy transition. This finding is consistent with the observations of (Chowdhury et al., 2021) for India and China and (Nguyen and Kakinaka, 2019) for South Asian countries.

The results of estimating the GMM-PVAR model in relation to the determinants of GDP show that RE and ICT are determinants of BRICS countries such that a 1% increase in RE and ICT leads to rise the GDP by 0.60% and 2.07% with the 5% significance level, respectively. ICT has the largest coefficient compared to other variables, which indicates that the strengthening of ICT section leads to an increase in GDP. But the CO_2 variable has a negative effect on GDP, so that a 1% increase in CO_2 reduces GDP by 0.72% with 1% level of significance. In relation to the determinants of CO_2, it is clear that the increase in RE leads to the significantly expansion of carbon emissions. So that 1% increase in RE enhance CO_2 emissions by 1.04%. But GDP and ICT do not have significant relationship with the carbon emissions of BRICS countries. Also, according to the results, GDP is the only variable that has a significant relationship with ICT. Therefore, ICT is up by 1.40% due to a 1% increase in GDP. While other variables (RE and CO_2) have no significant relationship with ICT.

As a next step, by applying the stability test to the GMM-PVAR model, the stability conditions of the model can be determined (Usman et al., 2022). According to Fig. 1, since modulus of eigenvalue's values are less than one and the covariates of the estimated model are located in the circle perimeter, the model has stability condition (Ozcan et al., 2020). Therefore, GMM-PVAR estimates are valid.

4.3. Generalized impulse response function and panel granger causality

In Fig. 2, the OIRFs chart evaluated for model. In fact, the responsive shocks of each dependent variable to four endogenous variables show in Fig. 2, which measured over eight periods. In the figure, the confidence interval with the blue area is shown, while the red line shows the response function. The connection between RE and CO_2 indicate that RE responds positively to CO_2 shocks. In the opposite link, the findings infer that the response of CO_2 to RE shocks is positive. Based on the results, GDP responses to RE shocks are constant up to period 5 but then increase to period 7 and after that decline, and RE responds negatively to GDP. Also, RE decrease as a response to ICT shocks, and the response of ICT to RE shocks indicate an increase of ICT.

In Table 5, the causal relation between the variables is analyzed. For this reason, the panel Granger causality test developed by (Dwivedi et al., 2022) (DH) has been used. This test shows more reliable and stable results in terms of cross-sectional dependence (Akbas et al., 2013; Feenstra et al., 2015). It should be noted that the results are approximately equal between W_{bar} and Z_{bar}. Following the finding shown in Table 5, there is bidirectional causality relationship from energy transition (RE) to GDP. The bidirectional causality is confirmed for both

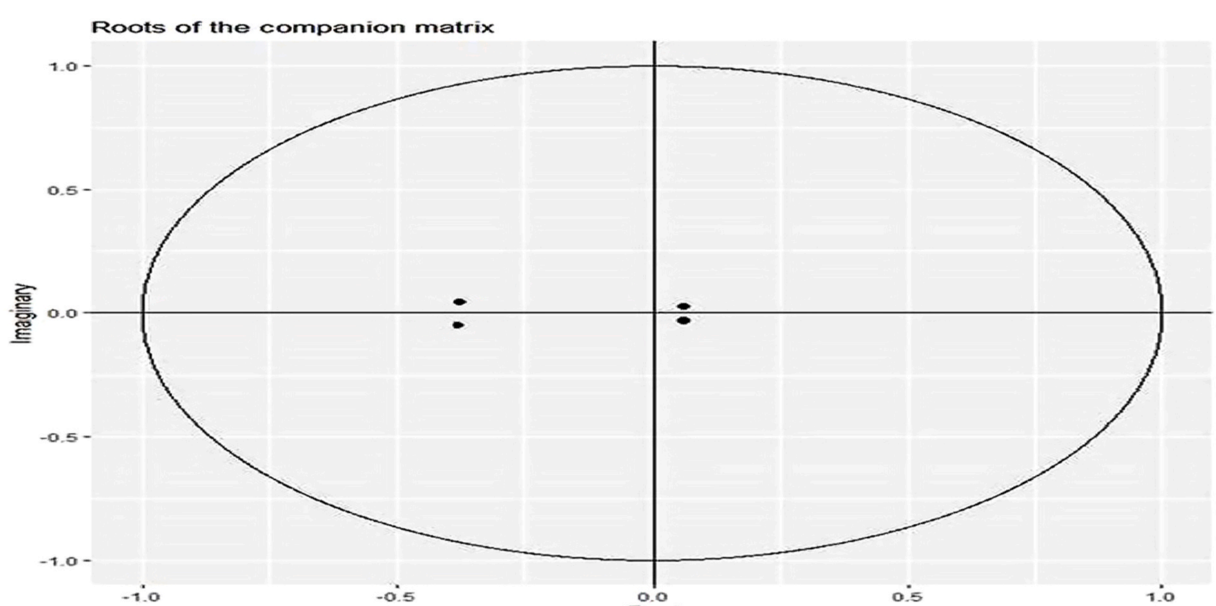

Fig. 1. Stability test.

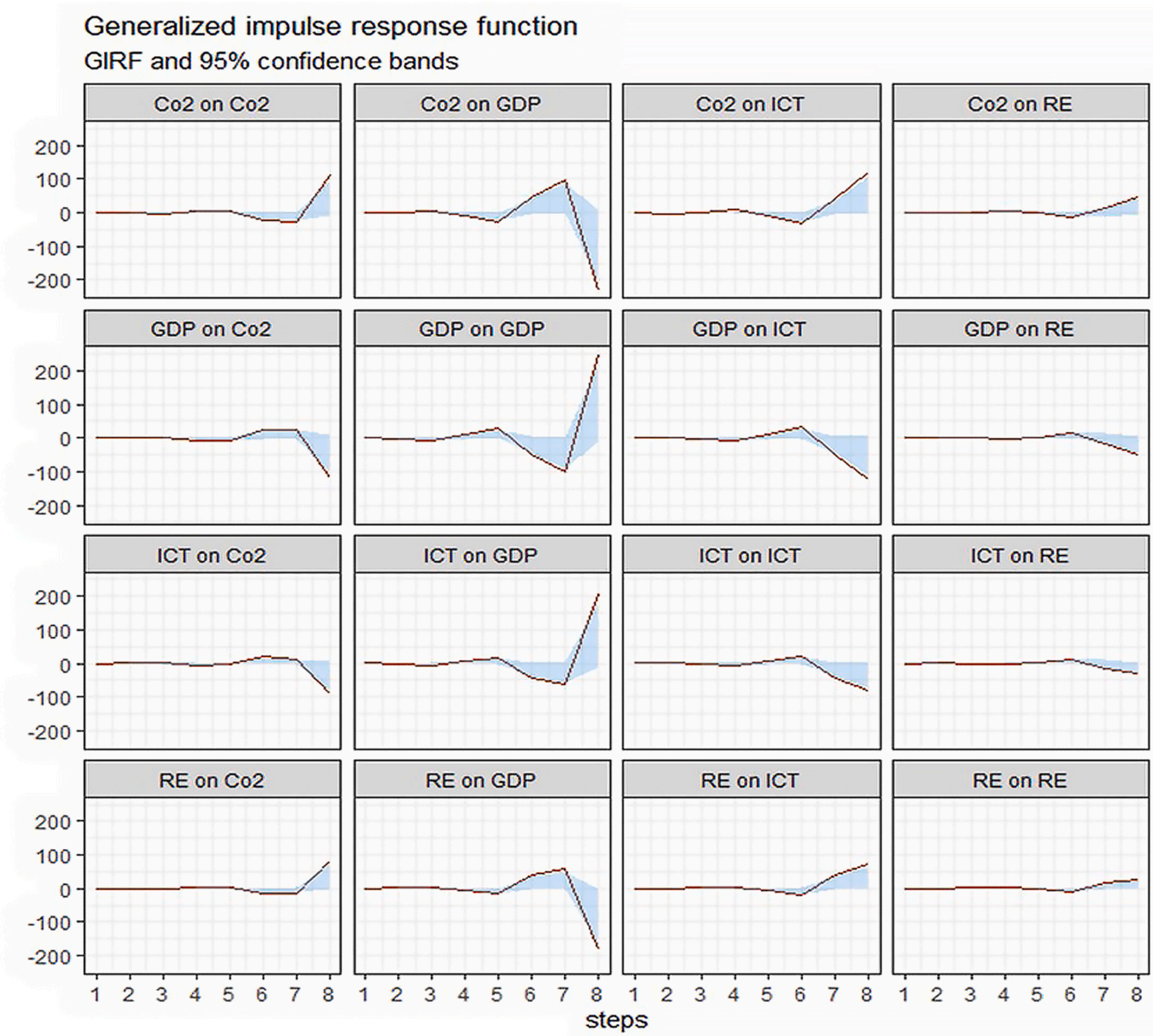

Fig. 2. Orthogonalized impulse response function (OIRFs).

Table 5
Panel Granger causality test - (Dwivedi et al., 2022).

Variables	RE		GDP		CO_2		ICT	
	W_{bar}	Z_{bar}	W_{bar}	Z_{bar}	W_{bar}	Z_{bar}	W_{bar}	Z_{bar}
RE	–	–	6.08***	4.57***	2.72***	0.80	6.99***	5.58***
GDP	5.28***	3.67***	–	–	6.53***	5.06***	7.07***	5.67***
CO_2	5.03***	3.38***	4.50***	2.79***	–	–	7.84***	6.53***
ICT	2.46**	0.52	12.03***	11.21***	4.34***	2.62***	–	–

Notes: *** and ** depict significance at a 1%, and 5% level, respectively.

tests. Enhancement GDP seems to play a role in the development of renewable energy and vice versa. These findings are in line with the results of several papers (Marques et al., 2010). In addition, unidirectional causality from RE to GDP was verified by (Amri, 2017; Banday and Aneja, 2020; Ben Mbarek et al., 2018), while (Azam et al., 2021) have reported a unidirectional causality from GDP to RE. Finally, a non-causal relation among RE and GDP was supported by (Su et al., 2021). In addition, empirical results found a bidirectional causality between energy transition to CO_2. RE and CO_2 beseem to have predictive power over each other. This result is similar to the findings of (Dulal et al., 2013; Baloch et al., 2019) for BRICS countries and (Chen et al., 2019) for China. But (Cherni and Jouini, 2017; IRENA (International Renewable Energy Agency), 2020; Uzar, 2020a) found that there is no causal relation between RE and carbon emission.

Lastly, the results reel that the renewable energy is cause of Granger ICT, and vice versa. Thus there is a complementary relationship between ICT and RE. The implication is that the development of the ICT sector will increase the deployment of renewable energy in BRICS countries. A bidirectional causality from ICT to RE was obtained by (Charfeddine and Kahia, 2021). Also (Caglar et al., 2021), has indicated a unidirectional causality from ICT toward RE. Causality testing is the most important step in examining the macroeconomic relationship between energy transition, GDP, carbon emissions, and ICT, which is useful for BRICS countries in developing energy transition.

5. Discussion

The vital outcomes of this research are the implications of energy-efficient ICT mechanisms in order to ameliorate environmental quality. In fact, ICT can increase the share of renewable energy in the total level of energy consumption and promote energy efficiency. Over the past two decades, BRICS economies have seen considerable growth in ICT. The expansion of the ICT sector can be crucial in maximizing the production of renewable resources. Additionally, it can also be used to comfort the storage of electricity generated from renewable sources. Especially, BRICS countries must apply renewable energy sources in ICT mechanisms which will led to importantly decreases of CO_2 emissions. Hence, the modification of nonrenewable energy consumption to renewable energy consumption is recommended through powering electricity websites and ICT equipment. Another crucial finding is the relationship between economic development and ICT. Within this context, BRICS countries can employ technological innovation in ICT industry. Adopted innovative technologies in ICT industry has a stimulating ability to improve the quality of environmental framework. Innovation is linked by the use of energy sources owing to the fact that enhances energy efficiency. Therefore, developing technology innovations and applying them in ICT industry by using renewable energy sources BRICS countries foster to boost economic growth and environmental quality.

Except for aggregate factor, each BRICS country should focus on specific renewable energy sources and ICT growth. Precisely, Brazil is third hydroelectricity producer all over the world. Also, it has abundant of renewable and natural sources such as hydraulic energy, wind, solar energy, ethanol, biodiesel and hydroelectric plants. Russia has a copious natural resource (such as natural gas and petroleum) and geographical conditions are favorable for wind stations. India as a tropical country can focus on solar energy. Biomass and wind sources are potential renewable energy resources generation of China. Finally, South Africa has the highest proportion of solar energy worldwide (Shah et al., 2022; Bano et al., 2022).

Regarding the ICT development, Russian and South Africa ICT services market are the lowest of BRICS countries. A major factor of Russian level is the rejection to collaborate with Western countries. Russia follows a lonely road on this field and particularly in public, military and industrial section. Last years, South Africa has higher growth rates on the ICT market which is related with the mobile apps market. Chinese ICT market emerges a rapidly growing which is stimulating by mobile application market growth and online gaming market (it's the largest worldwide). India is the second largest ICT market in Asia-Pacific area. It subsidizes on technological projects and computer software. Moreover, India government funds both public and private companies. Finally, Brazil ICT market is the first in Latin America and sixth worldwide. It funds technological innovation, trade policy and industrial services (such as software) (Biryukova and Matiukhina, 2019).

6. Conclusions and policy implications

The aim of this paper is to analyses the nexus between energy transition, economic growth, carbon emissions, and ICT using data from 2000 to 2017 for BRICS countries. The novel GMM-PVAR method has been used to achieve this goal. In addition, the interrelationships between the research variables are evaluated using the panel Granger causality test developed by (Geng and Ji, 2016).

The results obtained from the PVAR-GMM analysis implicate a positive and significant impact of CO_2 emission on energy transition. Increased economic activity in emerging BRICS countries to achieve high economic growth has led to increased carbon emissions and further environmental degradation. Therefore, it causes the transition of non-renewable energy toward renewable energy in BRICS economies and increases renewable energy consumption. Additionally, economic growth (GDP) shows positive impacts on renewable energy. Increasing a BRICS countries GDP and income can increase the demand for the deployment of renewable energy/energy transition. Finally, ICT promotes the development of renewable energy. Therefore, in addition to economic and environmental factors, technological factors also have a role in energy transition. According to the panel Granger causality test findings, there is bidirectional causality between GDP and RE, and CO_2 and RE. Furthermore, the results of DH causality test demonstrated that there is bidirectional causality between ICT and energy transition.

Therefore, the results of this research can provide valuable points for policymakers. Since ICT leads to the clean energy transition, thus results call for government intervention to develop ICT across the BRICS country. BRICS economies must therefore provide financial support R&D projects to expand the ICT sector in order to renewable energy development. In addition, BRICS governments importing ICT products through foreign direct investment and reducing taxes on them can lead to the development of green and sustainable energy. Therefore, such regulations for trade in ICT goods can boost renewable energy consumption in BRICS economies.

In addition, and regarding the environmental policy implications, BRICS countries require to apply the next suggested policies to ameliorate the environmental tax section in order to accomplish environmental sustainability targets. Particularly, employing taxes is productive in urging enterprises to alter their energy source streams and rise the costs of nonrenewable and energy-intensive goods. Apart from that, these taxes as emission abatement actions supply forceful privileges for the ingenuity and R&D. Furthermore, to attain the highest profit from the environmental taxes, the BRICS governments must assure the severe implication of the environmental regulations with the enhanced quality of governance to meet global criterions. Lastly, each policy maker can derive advantage from the taxes and fund renewable productivity infrastructure of BRICS countries.

The present study, like other studies, has limitations. Therefore, other researchers are suggested to first examine the nexus energy transition, GDP, CO_2 emissions, and ICT in other countries and economic regions (such as the countries of the MENA region, Latin America and Caribbean region, developed countries G-7, etc.). Second, it is suggested that future studies can achieve significant results by including technological factors such as R&D and renewable energy power capacity, and political factors such as institutional quality. This enriches the experimental literature and analyses the stability of the outputs of previous researches.

CRediT authorship contribution statement

Panayiotis Tzeremes: Methodology, Writings. **Eyup Dogan:** Supervision, Model. **Nooshin Karimi Alavijeh:** Writings, Data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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