Exploring the effect of renewable energy on low-carbon sustainable development in the Belt and Road Initiative countries: Evidence from the spatial-temporal perspective

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Abstract

The Belt and Road Initiative (BRI) has promoted the deployment of renewable energy to achieve sustainability. It is essential to reveal the influence of renewable energy on low-carbon economic development. The share of renewable energy consumption (SREC) is taken as the core explanatory variable in this paper, and its impacts on carbon emission intensity (CEI) and economic growth are investigated from the spatial-temporal perspective. First, the panel Granger causality test is applied for revealing the causal links among SREC, CEI, and economic growth during 1999-2017. Then, this paper investigates the impacts of SREC on economic growth and CEI through rigorous econometric techniques. Based on the regression results, Shapley value decomposition is utilized to account for the cross-country inequalities of economic growth and CEI.

The main findings are as follows: (1) There exist bidirectional Granger causalities between SREC, economic growth, and CEI, which shows there is a systematic link between the three variables. (2) All models demonstrate the inverted U-shaped nexus between SREC and economic growth, indicating renewable energy deployment costs are urgent to be decreased with SREC increasing. Besides, capital investment and openness positively affect economic growth, but energy intensity has an opposite impact. (3) From the spatial heterogeneity perspective, the cross-country inequality in economic growth is primarily due to the regional inequality of capital investment, followed by energy intensity and SREC. By contrast, the impacts of labor and openness are negligible. (4) SREC has a negative effect on CEI. In addition, an inverted U-shaped
nexus between economic growth and CEI is observed. Energy intensity positively affects CEI, while the impacts of urbanization and openness are insignificant. (5) From the spatial heterogeneity perspective, the cross-country CEI inequality is mostly caused by the inequality of energy intensity, followed by SREC, urbanization and economic growth, while the contribution of the openness gap is little. This article provides important implications for low-carbon development in the BRI countries.

**Keywords:** Renewable energy; Low-carbon sustainable development; Spatial-temporal heterogeneity; GMM; Regression-based Shapley value decomposition

**Introduction**

Since the industrial revolution, economic growth has been accompanied by a large amount of fossil energy, which not only results in a large number of air pollutants but also causes a variety of greenhouse gases. Global warming has become an important environmental issue affecting human well-being. According to the United Nations Framework Convention on Climate Change (UNFCCC 1992), both developed and developing countries have obligations to reduce carbon emissions. In 2015, the Paris Agreement issued by the Paris Climate Change Conference made arrangements for addressing global warming after 2020 (UNFCC 2015). The Paris Agreement aims to control the rise in global temperature lower than 2°C relative to the pre-industrial period. To curb global warming, improving energy structure and promoting energy transition towards a clean and low-carbon mode has increasingly become an international consensus. The global renewable energy consumption increased by 512 million tonnes oil equivalent during 2000-2018, of which the average annual growth rate is 14.47% (BP 2019).

The Belt and Road Initiative (BRI) was put forward by China in 2013. At present, the BRI covers 65 countries from Asia, Europe and Africa, accounting for 62% of the total population, 30% of GDP, and 50% of primary energy consumption in the world (Qi et al. 2019). Energy-related issues have gained considerable attention (Yao et al. 2019). It is predicted that the electricity demand of BRI countries will continue to grow rapidly, and by 2020 the power generation will increase by 70% from the 2016 level.
Green and low-carbon development is an important connotation of the BRI, which requires protecting the ecological environment and promoting sustainable development. International energy cooperation no longer emphasizes traditional fossil energy mining, rather, renewable energy is a critical task in energy cooperation among the BRI countries. It is predicted that the total renewable energy installed capacity of 38 BRI countries may reach 644.334 GW, and the total investment in wind power and solar energy may reach 644.334 billion US$ (CNEIA 2019). Under the carbon emission reduction targets mandated by the Paris Agreement, the newly installed capacity of renewable energy in countries along the BRI in 2030 is expected to reach 3.5 trillion kWh (Jing et al. 2020).

In terms of energy endowment, countries along the BRI are rich in renewable energy resources. Europe is the most developed region for wind energy utilization. In Asia and Africa, the theoretical reserves of hydropower, wind energy, and solar energy exceed half of the global reserves. Central Asia and some Southeast Asia countries such as Thailand, India, and the Philippines have good sunlight resources. These regions are suitable for building large-scale solar power stations. On the whole, the potential of renewable energy deployment in these BRI countries is huge. Meanwhile, the growing renewable energy is a key way to mitigate global warming and meet the growing energy demands. Does the development of renewable energy pay high economic costs? Is it effective in mitigating carbon emissions (i.e. CEs)? How to account for the spatial heterogeneity? What are the mechanisms behind them? These questions remain to be further studied.

The existing literature lacks the consideration of endogeneity problems caused by reverse causalities between renewable energy consumption (i.e. REC), economic growth (i.e. EG), and carbon emission intensity (i.e. CEI). Most studies investigate the driving factors from the temporal perspective, while little research focuses on spatial heterogeneity analysis. Taking the BRI as an example, this paper clarifies the influence mechanisms of renewable energy development (represented by the share of REC, i.e. SREC) on EG and CEI, and provides decision support for policymaking. This paper extends the literature from the following aspects. (1) Based on the analysis of the
influence mechanisms, this paper analyzes the bidirectional Granger causalities between SREC, CEI, and EG, using the sample data of 28 BRI countries during 1999-2017. (2) This paper combines econometric analysis and Shapley value decomposition to study the spatial-temporal drivers of EG and CEI. (3) Furthermore, this paper establishes both static and dynamic panel models simultaneously, and then employs some robust econometric techniques, including two-stage least squares estimation (2SLS), difference-GMM and system-GMM, to investigate how SREC affects CEI and EG, respectively. (4) Based on the regression results, this study empirically accounts for the regional disparities of EG and CEI through the Shapley value decomposition.

The rest content of this article is presented in the next parts. The second part reviews the relevant literature. The third part introduces the research methods adopted in this paper. As for the fourth part, it analyzes the influence mechanisms among EG, CEs, and REC, and then describes all variables and relevant data sources. The fifth part presents the empirical results and provides in-depth discussion. In Section 6, we conclude this study and obtain some important implications.

**Literature review**

Under the background of global energy transition, most countries regard renewable energy as an important strategic energy resource (Lund 2007). Renewable energy deployment is related with the well-being of human beings. It will inevitably bring profound changes to economic and social development, and is extremely significant in addressing climate change and improving the future living environment. Therefore, the development of renewable energy has attracted broad research attention. Scholars worldwide have made relevant research on the associations among renewable energy, economic, social, and environmental factors from dissimilar perspectives. Among these, two important issues are worthy of in-depth study. The first one is the role of renewable energy development in mitigating global warming (Arent et al. 2011), while the other is the economic impacts of renewable energy development (Jenniches 2018). This paper reviews related research strands to find the deficiencies of the existing literature. The existing research is conducted from the following aspects.
Energy is extremely important in supporting EG. The EG-REC nexus has generated abundant research interest (Liu and Hao 2018). However, there is no agreement among the academic community on their relationship, including the existence of causality and its direction. Some scholars find renewable energy is beneficial to EG (Ito 2017; Wang and Wang 2020). In contrast, other scholars state that renewable energy hinders EG (Ocal and Aslan 2013). For example, using the data of 15 West African countries during 1995-2014, Maji et al. (2019) investigate the impact of renewable energy on EG and find that renewable energy is adverse to EG. This is because the consumption of unclean and inefficient renewable energy such as wood biomass reduces productivity and hinders EG. However, some evidence shows renewable energy has little impact on EG in the short term and long term (Menegaki 2011; Razmi et al. 2020). In turn, EG may also affect renewable energy. For example, Yao et al. (2019) reveal a U-shaped curve nexus between REC and EG. Fan and Hao (2019) find that GDP per capita growth rate negatively influences REC per capita growth rate, while the latter has little impact on the former. Additionally, scholars also confirm that a bidirectional causality exists between REC and EG (Apergis and Patne 2010; Kahia et al. 2016; Liu and Hao 2018; Shahbza et al. 2015). Regarding research methods, scholars have utilized various econometric models to study the REC-EG nexus, such as fixed effects estimation, panel cointegration, autoregressive distributed lag (ARDL) approach, panel threshold model. However, little study considers the endogeneity problems in the econometric models, which can lead to biased estimation results.

Renewable energy has overall environmental impacts on resources and ecosystems (Mahmud et al. 2020). Many studies have investigated the relationships between different environmental indicators and renewable energy (Khan et al. 2020). Scholars have conducted extensive studies on the environmental benefits of REC. For example, based on 28 EU countries from 1995 to 2015, Akadiri et al. (2019) argue that the development of renewable energy is a reliable path to reduce environmental pollution. Nathaniel and Khan (2020) use the ecological footprint to represent environmental quality and reveal that REC is conducive to improving environmental quality. Similar
findings have been confirmed in other studies (Sharif et al. 2020). Specially, it is believed that renewable energy development has the dual benefits of reducing CEs and mitigating air pollution. For example, the CGE model is employed by Xie et al. (2018) to study how renewable energy affects CO$_2$, SO$_2$, and NO$_X$ emissions in China’s Beijing-Tianjin-Hebei region. They argue that renewable energy can reduce CO$_2$ and pollutant emissions, and the emission reduction rate can reach 10%-40% under different scenarios. On the whole, with regard to the environmental impacts of renewable energy development, most studies focus on its impact on CEs (Apergis et al. 2010; Irandoust 2016; Jarke and Perino 2017; Wang et al. 2020). Destek and Aslan (2020) investigate how different renewable energy types influence CEs in G7 countries. They find that hydropower, biomass energy and wind energy are effective in reducing CEs, while the effect of solar energy is not significant. By contrast, CEs also have some effects on renewable energy (Marques et al. 2010; Wang et al. 2018). In addition, some evidence illustrates that a bidirectional causal link exists between CEs and REC (Dogan and Seker 2016).

The links between EG, CEs and REC have received considerable attention (Mbarek et al. 2018; Saidi and Mbarek 2016). Taking the United States as the research object, Menyah and Wolderufael (2010) study the causal relationships between EG, CEs, and REC through the modified Granger causality test. Similarly, Jebli et al. (2016) investigate the causalities among renewable energy, non-renewable energy, GDP and CEs per capita in 25 OECD countries. In addition, Bento and Moutinho (2016) study the relationships between EG, CEs, non-renewable and renewable electricity generation. They find no causality between renewable electricity and EG and CEs. Many studies emphasize revealing the impacts of REC on CEs or EG, while CEs and EG in turn have important impacts on REC (Sadorsky 2009). Therefore, the endogeneity problems caused by reverse causalities should be fully considered and addressed in the econometric models.

Through the review of related literature, it is found that there is no consensus about how REC affects EG or CEs, given that scholars may use different samples and research methods. Furthermore, little research considers the endogeneity problems caused by the
reverse causalities between the three variables, thereby resulting in biased estimation
results. More importantly, most studies investigate the driving factors from the temporal
perspective, while little research focuses on spatial heterogeneity analysis. Compared
with the existing literature, this paper not only obtains some new and meaningful
findings with regard to the relationships between SREC, EG and CEI from the spatial-
temporal perspective, but also solves the endogeneity problems, thereby making the
estimation results more robust and reliable. This study is beneficial for the BRI
countries to promoting renewable energy development, participating in global carbon
emission reduction, and achieving sustainable economic development.

Methodology

Panel Granger causality test

Granger causality test is a useful tool for judging whether statistically significant
causalities exist among variables. Let \( x_t \) and \( y_t \) be two time series respectively,
based on the study of Granger (1969), the following model can be applied to investigate
whether \( x \) is the cause of the change in \( y \):

\[
y_t = a + \sum_{k=1}^{K} \gamma_k y_{t-k} + \sum_{k=1}^{K} \beta_k x_{t-k} + \epsilon_t, \quad t = 1, ..., T
\]

(1)

Where \( y_{t-k} \) refers to the k-order lagged term of \( y \), and \( \gamma_k \) represents its
coefficient; \( x_{t-k} \) indicates the k-order lagged term of \( x \), and \( \beta_k \) is its coefficient. \( \epsilon_t \)
denotes the error term. \( a \) denotes the constant term. The null hypothesis is \( \beta_1 = \cdots = \beta_K = 0 \).
F statistics are applied to examine the null hypothesis. The alternative
hypothesis indicates that a causal link exists between \( x \) and \( y \), that is, \( x \) Granger
causes \( y \). Following the similar way, it is feasible to examine whether \( y \) is the Granger
cause of \( x \). Furthermore, Dumitrescu and Hurlin (2012) provide a Granger causality
test method for panel data. The basic model is expressed below:

\[
y_{i,t} = a_i + \sum_{k=1}^{K} \gamma_{i,k} y_{i,t-k} + \sum_{k=1}^{K} \beta_{i,k} x_{i,t-k} + \epsilon_{it}, \quad t = 1, ..., T
\]

(2)

Therein, \( i \) represents the \( i \)-th country, \( t \) indicates time, \( i = 1, ..., N \); \( t = 1, ..., T \). The Dumitrescu-Hurlin test provides a null assumption that \( \beta_{i1} = \cdots = \beta_{ik} = 0, \forall i = 1, ..., N \).
This article checks the causal dynamics between SREC, EG, and CEI through the following VAR model:

\[ \begin{align*}
\text{EG}_{i,t} &= a_i + \sum_{k=1}^{K} g_{ik} \text{EG} + \sum_{k=1}^{K} b_{ik} \text{SREC}_{i,t-k} + \sum_{k=1}^{K} \alpha_{ik} \text{CEI}_{i,t-k} + e_{it} \\
\text{SREC}_{i,t} &= a_i + \sum_{k=1}^{K} g_{ik} \text{SREC} + \sum_{k=1}^{K} b_{ik} \text{EG}_{i,t-k} + \sum_{k=1}^{K} \alpha_{ik} \text{CEI}_{i,t-k} + e_{it} \\
\text{CEI}_{i,t} &= a_i + \sum_{k=1}^{K} g_{ik} \text{CEI} + \sum_{k=1}^{K} b_{ik} \text{EG}_{i,t-k} + \sum_{k=1}^{K} \alpha_{ik} \text{SREC}_{i,t-k} + e_{it}
\end{align*} \] (3)

Therein, EG refers to economic growth represented by GDP per capita, SREC represents the share of renewable energy consumption, CEI represents carbon emissions intensity (namely CEs per unit of GDP). \( \alpha \), \( \beta \), and \( \gamma \) are estimated coefficients.

**SREC-EG model**

**Static econometric model for SREC and EG**

The Cobb-Douglas production function is a useful research tool in microeconomics. It has been widely adopted in energy economics-related research. This paper uses Solow’s neoclassical growth theory (Solow 1957), coupled with the Cobb-Douglas production function, to construct an economic growth model as:

\[ Y = A^{\beta_1} K^{\beta_2} L^{\beta_3} \] (6)

Where \( Y \) represents economic output, \( L \) represents labor input, \( K \) represents capital, \( A \) represents technological level. \( \beta_1 \), \( \beta_2 \) and \( \beta_3 \) reflect the degree of the impacts of these variables on economic output. In addition, energy is an important production factor. The growing renewable energy is helpful in optimizing energy mix, increasing employment, and upgrading the industrial structure. Studies have shown that renewable energy development is influential in the process of economic development (Rahman and Velayutham 2020; Saidi and Omri 2020). Additionally, opening to our outside world is conducive to attracting foreign investments, promoting exports, and introducing advanced production and management technologies. Accordingly, openness degree may significantly affect EG. Therefore, this paper integrates renewable energy development and openness degree into Eq. (6), and obtains the following extended model:

\[ Y = A^{\beta_1} K^{\beta_2} L^{\beta_3} OPN^{\beta_4} SREC^{\beta_5} m \] (7)
Where SREC represents the share of renewable energy consumption. OPN denotes the degree of openness. $\mu$ is the random error term. Meanwhile, to examine whether there exists a non-linear relationship, the quadratic term of SREC is introduced into the econometric model. Applying natural logarithmic transformation to Eq. (7) will yield the following static panel model:

$$\ln EG_{it} = \beta_0 + \beta_1 \ln EI_{it} + \beta_2 \ln CAP_{it} + \beta_3 \ln LAB_{it} + \beta_4 \ln OPN_{it} + \beta_5 \ln SREC_{it} + \beta_6 \ln SREC_{it}^2 + \gamma_t + \delta_i + \mu_{it}$$

(8)

Where $i$ indicates country, $t$ indicates time. EG denotes economic growth, i.e., GDP per capita. CAP is capital. LAB is labor. EI is energy intensity, which reflects the technological level. $\delta_i$ and $\gamma_t$ represent the regional and time non-observed effects, respectively. Eq. (8) is a two-way fixed effects model. $\beta_0$ is the constant term. $\beta_1, \beta_2, \cdots \beta_6$ are the corresponding coefficients of variables. $\ln$ indicates natural logarithm scale, which can relieve heteroscedasticity to some extent.

**Dynamic econometric model for SREC and EG**

The changes in economic factors are often inertial. That is to say, the previous EG may have a certain impact on that of the subsequent period. Therefore, the introduction of one-period lagged $\ln EG$ can better control the lagged effects. This paper establishes the following dynamic panel model:

$$\ln EG_{it} = \beta_0 + \beta_1 \ln EI_{it} + \beta_2 \ln CAP_{it} + \beta_3 \ln LAB_{it} + \beta_4 \ln OPN_{it} + \beta_5 \ln SREC_{it} + \beta_6 \ln SREC_{it}^2 + \gamma_t + \delta_i + \mu_{it}$$

(9)

The difference equation of formula (9) is as follows:

$$\Delta \ln EG_{it} = \beta_1 \Delta \ln EI_{it} + \beta_2 \Delta \ln CAP_{it} + \beta_3 \Delta \ln LAB_{it} + \beta_4 \Delta \ln OPN_{it} + \beta_5 \Delta \ln SREC_{it} + \beta_6 \Delta \ln SREC_{it}^2 + \beta_7 \Delta \ln EG_{i,t-1} + \Delta \gamma_t + \Delta \delta_i + \Delta \mu_{it}$$

(10)

Since fixed-effects estimation causes dynamic panel bias for dynamic panel model, this article adopts GMM methods to estimate dynamic panel models in this section, so as to resolve the endogeneity problems within the models. To be more specific, the difference-GMM method is used to estimate formula (10), while the system-GMM model estimates formulas (9) and (10) jointly. The advantages of GMM methods lie in the following aspects. (1) Difference-GMM can eliminate the individual effects and some variables that do not change with time, thereby alleviating the problem of missing variables to some degree. (2) System GMM approach can address the issue of time-
invariant missing variables in panel model. (3) When there exist some endogenous variables in the model, the instrumental variable estimation can obtain consistent estimation results. Moreover, using instrumental variables can effectively resolve measurement errors (Bond et al. 2001). However, GMM estimation also has some weaknesses. For example, GMM estimates have bad small sample properties, and they may cause bias and inefficiency in small samples. Besides, it is difficult to find some suitable instrument variables. Compared with the Arellano-Bond model (Arellano and Bond 1991) and Arellano-Bover/Blundell-Bond model (Blundell and Bond 1998), Windmeijer (2005)'s model can address low-order moving-average correlated errors in difference-GMM and system-GMM estimators. It should be noted that SREC is an endogenous variable in the above dynamic panel models. The lagged instrumental variables are adopted to perform GMM estimators.

**SREC-CEI model**

**Static econometric model for SREC and CEI**

According to the \( IPAT \) identity, population, affluence, and technology are primary factors influencing environmental quality.

\[
I = P \times A \times T
\]

Therein, \( I \) denotes the environment pressure represented by CEI in this paper. \( P \) represents population factor, \( A \) represents affluence factor, \( T \) refers to technological factor. On basis of the \( IPAT \) model, the \( STIRPAT \) (stochastic impacts by regression on population, affluence, and technology) model (Dietz and Rosa 1997) can be formulated as:

\[
I = aP^bA^cT^d \mu
\]

Where \( a \) refers to the constant term; the exponents reflect the magnitudes of the impacts of different determinants on \( I \). \( \mu \) is the random disturbance item. This paper utilizes the urbanization level to represent the impact of population factor. In addition, EI is used to denote technological factor, and GDP per capita is used to represent affluence factor. To examine the environmental Kuznets curve (EKC) hypothesis between economic growth and carbon emissions (Sharif et al. 2018), the quadratic term of GDP per capita is also included. Besides, openness degree is also an important
influencing factor of CEI (Dong et al. 2018a). On the basis of the natural logarithmic transformation of both sides of Eq. (12), we have the following static panel model for CEI:

\[
\ln CEI_{it} = \beta_0 + \beta_1 \ln URB_{it} + \beta_2 \ln EI_{it} + \beta_3 \ln SREC_{it} + \beta_4 \ln OPN_{it} + \beta_5 \ln EG_{it} + \beta_6 \ln EG_{it}^2 + \gamma_t + \delta_i + \mu_{it}
\] (13)

Where URB denotes urbanization level. The meanings of SREC, EI, OPN, EG, \( \delta_i \), and \( \gamma_t \) are the same with these in Eq. (8). Eq. (13) is a two-way fixed effects model. \( \beta_0, \beta_1, \beta_2, \ldots, \beta_6 \) are the parameters to be estimated.

**Dynamic econometric model for SREC and CEI**

There is evidence that the previous CEI may have some impacts on the current CEI (Dong et al. 2018a). Given the possible lagged effect of CEI, a dynamic panel model is constructed for CEI:

\[
\ln CEI_{it} = \beta_0 + \beta_1 \ln URB_{it} + \beta_2 \ln EI_{it} + \beta_3 \ln SREC_{it} + \beta_4 \ln OPN_{it} + \beta_5 \ln EG_{it} + \beta_6 \ln EG_{it}^2 + \gamma_t + \delta_i + \mu_{it}
\] (14)

\[
\Delta \ln CEI_{it} = \beta_1 \Delta \ln URB_{it} + \beta_2 \Delta \ln EI_{it} + \beta_3 \Delta \ln SREC_{it} + \beta_4 \Delta \ln OPN_{it} + \beta_5 \Delta \ln EG_{it} + \beta_6 \Delta \ln EG_{it}^2 + \gamma_t + \delta_i + \mu_{it}
\] (15)

Similarly, Eqs. (14) and (15) are also estimated by difference-GMM and system-GMM methods (Windmeijer 2005). SREC and EG are regarded as endogenous variables.

**Shapley value decomposition**

The previous sections investigate the temporal variation of EG and CEI. In terms of economy, society, resources, and environment, there are huge differences between the BRI countries. In order to understand the regional differences of EG and CEI among different countries, this paper employs a regression-based Shapley decomposition (Wan 2002, 2004) to analyze the drivers of EG and CEI from the spatial heterogeneity perspective. This paper adopts the Gini coefficient to measure the spatial differences of EG and CEI among the BRI countries.

\[
GE = \frac{\hat{A}^{EG} \cdot \hat{A}^{\text{EG}} | EG_i - EG_j |}{2n^2 \text{EG}}
\] (16)
Where $i$ and $j$ denote different BRI countries, $GE$ is the Gini coefficient reflecting the regional inequality of EG. $GC$ is the Gini coefficient reflecting the regional inequality of CEI. $\overline{EG}$ represents the average value of EG, $\overline{CEI}$ represents the average value of CEI.

Through the Shapley value decomposition, the inequalities of EG and CEI can be explained by their influencing factors. The Shapley value decomposition is conducted based on a given regression equation. The simplification of the decomposition process is presented as follows.

$$y = \varepsilon + \lambda \cdot X$$  \hspace{1cm} (18)

$$y = 0 \Rightarrow y^* = \lambda \cdot X$$  \hspace{1cm} (19)

$$y^* = \sum_{i=1}^{h} \lambda_i \cdot x_i + \sum_{i=1}^{h} \lambda_i \cdot x_i$$  \hspace{1cm} (20)

Where $y$ is the explained variable, $\varepsilon$ is the error term, $X$ denotes its determinants, $h$ indicates the number of determinants of $y$. Using the Shapley decomposition method (Shorrocks, 1999), the contribution of $\varepsilon$ to the inequality of $y$ can be calculated by

$$\Delta \varepsilon = \sum G \cdot y - G \cdot y^*$$  \hspace{1cm} (21)

Where $G$ denotes the Gini coefficient operator. The contribution of $x_i$ to the inequality of $y$ is given by

$$\Delta x_i = \sum G \cdot y^* - G \cdot y^{**}$$  \hspace{1cm} (22)

Based on Eq. (22), we can obtain the contribution of each influencing factor. Finally, the inequality of the dependent variable $y$ is attributed to the residual and different determinants.

**Variables and data sources**

**The influence mechanisms between REC, EG, and CEs**

**The REC-EG nexus**
As a production input factor, energy is critical for supporting EG. Along with the acceleration of energy transition globally, renewable energy has achieved rapid development in recent years. Renewable energy is becoming increasingly essential in the energy supply structure, and it possesses positive as well as negative impacts on EG (Dogan et al. 2020). The increasing renewable energy is able to create more employment opportunities and promote the growth of related sectors. However, the deployment of renewable energy requires a large number of investments in technologies and capital, which will result in large financial pressure and economic burdens. Notably, EG will stimulate renewable energy deployment as well. A higher economic level ensures that there are some advantages of technologies, capital and talents for renewable energy expansion, thereby reducing economic costs for growing renewable energy. Specifically, high-income countries may have sufficient scientific research personnel, R&D investment, abundant professional knowledge stock, and advanced environmental protection concepts. Moreover, it is easier for developed countries to attract the inflows of capital, technologies and talents, forming the agglomeration effect.

The REC-CEs nexus

REC and CEs have an interactive influence mechanism. Since the industrial revolution, fossil energy consumption has brought about a huge amount of greenhouse gas emissions. Fossil energy has serious negative environmental externalities, while renewable energy has the characteristics of large reserves and little pollution. Global warming urgently requires the transformation of energy consumption structure, which significantly prompts renewable energy deployment. Meanwhile, increasingly REC is a crucial way of decreasing CEs. In indeed, countries around all of the world have made active carbon mitigation efforts and formulated corresponding renewable energy development strategies. For example, the European Union proposes to increase SREC to at least 32% by 2030 (European Commission 2018). This paper aims at studying how SREC affects CEs.

The EG-CEs nexus

The EG-CEs nexus is frequently studied in the literature (Almulali and Sab 2012). Economic development requires consuming a lot of fossil energy, resulting in
tremendous CEs (Rauf et al. 2018b). However, the continuous transformation of industrial structure and optimization of energy consumption structure will gradually suppress the growth trend of CEs. On basis of the environmental Kuznets curve (EKC) theory, EG and CEs may present a relationship as an inverted U-shaped curve (Rauf et al. 2018a). Notably, there is a large amount of evidence that climate change negatively affects EG (Dell et al. 2012; Jiang et al. 2010; Richard 2018). According to the Paris Agreement, different countries set their voluntary emission reduction goals. For example, China plans to realize its peak CEs by 2030 and reduce CEI by 60% to 65% compared to the 2005 level (NDRC 2015). Carbon emission constraints will impose some restrictions on industrial production and increase emissions costs, which may negatively influence EG. Therefore, in this paper, the reverse causality between CEI and EG should be considered when analyzing the influence of EG on CEI.

Variable definitions and data sources

This research explores the effects of SREC on CEI reduction and EG in countries along the BRI. Given the data availability, the sample data used in this paper cover 28 BRI members and span the study period 1999-2017. According to the Cobb-Douglas production function and Solow’s neoclassical growth theory, six explanatory variables are introduced into the SREC-economic growth model, including capital, labor, energy intensity, openness, SREC and its quadratic term. Based on the extended STIRPAT model, six explanatory variables are introduced into the SREC-CEI model, namely urbanization, energy intensity, openness, SREC, economic growth and its quadratic term. All variables in this paper are listed in Table 1. Specifically, total renewable energy consumption (i.e. REC) is calculated as the sum of hydropower, wind, solar, geothermal and biomass energy. The data of carbon emissions and energy consumption come from the Statistical Review of World Energy (BP 2019). GDP, urbanization, exports, and labor are obtained from World Bank (2019). Specially, the data of capital stock are derived from www.ggdc.net/pwt.

Renewable energy development is the core explanatory variable, which is represented by the share of REC (i.e. SREC). Fig. 1 illustrates the spatial distribution

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1 The 28 BRI countries comprise Bangladesh, Bulgaria, China, Croatia, Czech, Egypt, Greece, Hungary, India, Indonesia, Iran, Kazakhstan, Latvia, Lithuania, Malaysia, Pakistan, Philippines, Poland, Romania, Russian, Singapore, Slovakia, Sri Lanka, Thailand, Turkey, Ukraine, Uzbekistan, and Vietnam.
of SREC of the 28 BRI countries in 1999, 2005, 2011 and 2017. On the whole, SREC shows a distinct increasing trend. For example, China’s SREC increases from 4.3% in 1999 to 11.48% in 2017. As shown in Fig. 1a, in 1999, the lowest SREC reported by Singapore was 0.16%, while the highest was 24.23% in Sri Lanka. Fig. 1d presents that Singapore still had the lowest SREC in 2017 at 0.28%, slightly higher levels of SREC were recorded in Bangladesh (0.9%) and Iran (1.46%). By contrast, Latvia had the highest SREC of 29.82% in 2017, followed by Vietnam (21.25%) and Croatia (19.86%).

Table 1
Definitions of variables appeared in the paper

| Variable                  | Definition                                                                 | Symbol |
|---------------------------|---------------------------------------------------------------------------|--------|
| Economic growth           | Per capita GDP                                                            | EG     |
| Carbon emissions          | CO₂ emissions                                                             | CEs    |
| Renewable energy consumption | The sum of hydropower, wind, solar, geothermal and biomass energy       | REC    |
| Carbon emission intensity | CEs per unit of GDP                                                       | CEI    |
| Renewable energy development | The share of REC                                                       | SREC   |
| Capital                   | Capital stock                                                             | CAP    |
| Labor                     | The number of labor force                                                 | LAB    |
| Openness                  | The ratio of exports to GDP                                               | OPN    |
| Energy intensity          | Energy consumption per unit of GDP                                        | EI     |
| Urbanization              | The share of urban population in total population                         | URB    |
Results and discussion

Panel unit root test and co-integration test

The existence of non-stationary variables may result in the problem of spurious regression. In fact, most economic variables in their original forms are non-stationary. Hence, it’s essential to conduct the unit root test for variable sequences. The cross-section heterogeneity should be considered in panel unit root test. There are two main forms of panel unit root tests. The first type supposes that various cross-sections share the common unit root. Another type supposes different unit roots for various cross-sections. To consider the two cases simultaneously, three methods are adopted, including LLC, IPS, and ADF tests. The null hypotheses of the three tests state that the checked variable sequence contains unit roots, i.e., non-stationary.

Table 2 exhibits the test results. On basis of whether there is a trend term, this paper has two specifications for each test. As shown in Table 2, from the perspective of the level sequence of each variable, some statistics imply the null assumption should
be accepted, indicating that the variable is a non-stationary sequence. As for the difference sequence of each variable, all statistics are significant, which means the first-order difference sequence of each variable is stationary. Overall, all variables are integrated in order 1. Then, the Kao test and Pedroni test are utilized for examining the co-integration relationships among these variables. Since variable sequences follow I(1) and there exist long-term co-integration relationships, it is feasible to conduct the following empirical analysis.

**Table 2**

Panel unit root test results

| Levels          | Series | LLC       | IPS        | Fisher-ADF |
|-----------------|--------|-----------|------------|------------|
| First difference|        | Constant  | Trend and intercept | Constant | Trend and intercept | Constant | Trend and intercept |
|                 |        |           |            |            |            |            |                |
|                 | EG     | -2.000**  | -4.056***  | 0.857      | 0.381      | -1.321     | 0.969        |
|                 | EG2    | -2.560*** | -4.124***  | 0.746      | -0.318     | -1.665     | 1.183        |
|                 | SREC   | -2.060*** | -7.018***  | -0.629     | -4.546***  | 1.400*     | 4.355***     |
|                 | SREC2  | -3.066*** | -7.200***  | -0.079     | -5.589***  | 1.707**    | 5.576***     |
|                 | CAP    | 0.999     | -6.844***  | 3.307      | -2.125**   | -0.903     | 6.820***     |
|                 | LAB    | -2.523*** | -6.387***  | 2.541      | -1.593*    | 1.421*     | 1.454*       |
|                 | OPN    | -2.620*** | -1.849***  | 0.874      | -1.701**   | 0.073      | 2.633**      |
|                 | EI     | -4.267*** | -3.332***  | 1.542      | -1.664**   | 0.116      | 3.075***     |
|                 | CEI    | -4.855*** | -3.807***  | 1.967      | -2.877***  | -2.600     | 2.435***     |
|                 | URB    | -10.212***| 0.870      | -10.759*** | 3.223      | 31.770***  | -0.317       |
|                 | EG     | -9.394*** | -7.029***  | -7.373***  | -4.784***  | 6.781***   | 4.350***     |
|                 | EG2    | -9.249*** | -6.991***  | -7.320***  | -6.147***  | 7.161***   | 4.429***     |
|                 | SREC   | -14.961***| -12.264*** | -15.472*** | -12.025*** | 25.212***  | 20.262***    |
|                 | SREC2  | -15.482***| -11.236*** | -16.143*** | -11.906*** | 27.378***  | 21.587***    |
|                 | CAP    | -4.274*** | -2.664**   | -1.490*    | -1.335*    | 6.774***   | 6.895***     |
|                 | LAB    | -11.183***| -9.681***  | -8.655***  | -6.842***  | 6.678***   | 3.706***     |
|                 | OPN    | -12.799***| -10.341*** | -12.239*** | -10.162*** | 19.862***  | 14.023***    |
|                 | EI     | -13.155***| -12.195*** | -12.626*** | -10.963*** | 16.238***  | 11.190***    |
|                 | CEI    | -12.528***| -12.749*** | -12.606*** | -11.477*** | 15.409***  | 9.091***     |
Note: The lags number is given by Akaike information criterion and Bayesian information criterion.

* implies p<0.10, ** implies p<0.05, *** implies p<0.01.

Table 3

Panel co-integration test results

| Model 1: SREC-EG | Kao test | Pedroni test |
|------------------|----------|--------------|
| ADF t statistic  | -1.877** | -5.797***    |

| Model 2: SREC-CEI | Kao test | Pedroni test |
|-------------------|----------|--------------|
| ADF t statistic   | 2.488*** | -9.072***    |

Note: ** denotes p<0.05, *** denotes p<0.01.

Results of panel Granger causality test

In regression analysis, endogeneity problems can lead to serious estimation bias. Endophytism is usually caused by the following three issues: missing variables, measurement errors, and reverse causality. Among them, reverse causality is usually ignored by scholars, thus obtaining biased results. In this study, reverse causality appears in the following ways. In the SREC-EG model, EG may lead to increasing SERC. In the SREC-CEI model, CEI may have some impacts on SREC and EG. Therefore, this paper employs the panel Granger causality test for the causalities among EG, SREC, and CEI. Table 4 displays the test results. As shown in Table 4, all the Zbar statistics are significant. It means that there are six Granger causalities, namely, there exists a bidirectional Granger causality among any two variables. Accordingly, their relationships are depicted in Fig. 2.

Table 4

Results of panel Granger Causality test

| H₀                                      | Zbar-statistic | Conclusion |
|-----------------------------------------|----------------|------------|
| EG doesn’t Granger cause SREC           | 5.406***       | Reject     |
| SREC doesn’t Granger cause EG           | 2.036**        | Reject     |
| CEI doesn’t Granger cause SREC          | 7.004***       | Reject     |
| SREC doesn’t Granger cause CEI          | 2.660***       | Reject     |
| EG doesn’t Granger cause CEI            | 10.862***      | Reject     |
| CEI doesn’t Granger cause EG            | 2.670***       | Reject     |

Note: ** refers to p<0.05, *** refers to p<0.01.
Results and discussion of the SREC-EG model

Table 5

Regression results of the SREC-EG model.

| Variables      | Model (1)          | Model (2)          | Model (3)          | Model (4)          | Model (5)          | Model (6)          |
|----------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|                | 2SLS               | 2SLS               | Diff-GMM           | Sys-GMM            | Diff-GMM           | Sys-GMM            |
| L.lnEG         | 0.903***           | 0.998***           | 0.771***           | 0.934***           |                    |                    |
|                | (0.013)            | (0.018)            | (0.044)            | (0.025)            |                    |                    |
| lnSREC         | -0.080***          | -0.389***          | -0.043***          | -0.094***          | -0.026**           |                    |
|                | (0.015)            | (0.067)            | (0.013)            | (0.011)            | (0.015)            | (0.014)            |
| (lnSREC)^2     | -0.040***          | -0.003*            | -0.004***          | -0.010***          | -0.003**           |                    |
|                | (0.008)            | (0.002)            | (0.001)            | (0.002)            | (0.002)            |                    |
| lnEI           | -0.442***          | -0.462***          | -0.024             | 0.0002             | -0.061             | 0.010              |
|                | (0.028)            | (0.028)            | (0.016)            | (0.023)            | (0.042)            | (0.035)            |
| lnCAP          | 0.502***           | 0.542***           | 0.074              | 0.001              |                    |                    |
|                | (0.024)            | (0.024)            | (0.011)            | (0.039)            |                    |                    |
| lnLAB          | -0.028             | -0.027             | 0.068              | 0.044              |                    |                    |
|                | (0.024)            | (0.024)            | (0.096)            | (0.043)            |                    |                    |
| lnOPN          | 0.044***           | 0.071***           | 0.038**            | 0.040***           |                    |                    |
|                | (0.019)            | (0.020)            | (0.042)            | (0.035)            |                    |                    |
| lnT            | 0.010***           | 0.010***           | 0.003              | 0.003              |                    |                    |
|                | (0.001)            | (0.001)            | (0.001)            | (0.004)            |                    |                    |
| AR(1)          | -2.919***          | -2.904***          | -2.921***          | -2.740***          |                    |                    |
| AR(2)          | -2.691***          | -2.696***          | -2.389***          | -2.563**           |                    |                    |
| AR(3)          | 0.622              | 0.494              | 0.628              | 0.670              |                    |                    |
| AR(4)          | 1.332              | 1.516              | 0.199              | 1.520              |                    |                    |
| Sargan test    | 24.370             | 22.554             | 23.678             | 23.809             |                    |                    |
| Wald chi2      | 54469.63*          | 934409.72**        | 74325.11**         | 668231.82*         |                    |                    |
| R^2            | 0.9026             | 0.9044             |                    |                    |                    |                    |
This paper establishes both static and dynamic panel models to explore the SREC-EG nexus. The regression results of the SREC-EG model are exhibited in Table 5. Specifically, the time fixed effects are considered by introducing the time trend term (i.e., $\text{Ln}T$ variable in Table 5). Model (1) and (2) present the estimation results obtained from the 2SLS method. Models (3)-(6) report the results obtained from GMM methods. On basis of the panel Granger causality test from Table 4, a bidirectional causality is found between EG and SREC. Therefore, $\text{lnSREC}$ is regarded as endogenous variables in the econometric models. Specifically, 2SLS, difference-GMM and system-GMM approaches are adopted for addressing the endogeneity problems. As shown in Table 5, although there are distinct differences in the magnitudes of estimated coefficients, the coefficients of the core explanatory variable (i.e. SREC) in Models (1)-(6) are all significant, and the coefficients signs of other determinants conform with theoretical expectations. Specially, $R^2$ reported in Model (1) and Model (2) is at least 90%, indicating that the models fit well. In particular, there is evidence to indicate a nonlinear nexus between SREC and EG.

Model (2) is estimated by using the lagged term of endogenous variable as the instrumental variable. As a comparison, Model (1) presents the fixed-effects estimation results. It can be seen from Model (1) and 2 that the elasticity coefficient of SREC is significantly negative, which is the same with its quadratic term. It is the evidence of a nonlinear inverted U-shaped nexus between SREC and EG. For many developing countries along the BRI, they are rich in hydropower and wind power resources. In order to boost low-carbon economic development, these countries actively develop clean energy and gradually lessen the use of traditional fossil fuels. These measures can

| Observation | 504 | 504 | 476 | 504 | 476 | 504 |
|-------------|-----|-----|-----|-----|-----|-----|
| Regional fixed effects | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| Time fixed effects   | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |

Note: (1) * represents $p<0.10$, ** represents $p<0.05$, *** represents $p<0.01$. (2) Standard errors are reported in brackets. (3) GMM estimations are obtained through the xtgd command in the STATA software. (4) AR statistics are the results of Arellano-Bond test. (4) In GMM estimators, the predetermined variable is $\text{lnEG}_{it-1}$, while the endogenous variables are $\text{lnSREC}$ and $\text{lnSREC2}$.
meet the growing energy consumption needs and control the production costs of enterprises. In addition, the deployment of clean energy requires tremendous fixed asset investments, which can drive steel, cement, machinery, and equipment manufacturing related industries. These contribute to promoting EG. Nevertheless, the excessive growth of renewable energy may not always be beneficial to EG. The optimal energy consumption strategy is that renewable energy and non-renewable energy exist at the same time (Tahvonen 1997). Renewable energy and non-renewable energy are not completely substituted. Currently, non-renewable energy is still the cornerstone of economic growth (See Fig.1). In fact, they follow the law of decreasing marginal technology substitution rate. As the difficulty and cost of factor substitution increase, the positive effect of factor substitution gradually decreases, and the marginal return on renewable energy input becomes negative. Moreover, the expansion of renewable energy imposes higher requirements on the power system. The long-distance transmission will increase the cost of electricity, and grid connection issues will affect the stable supply of power. Meanwhile, renewable energy projects require a large amount of capital investment, financing and subsidies, which increases financial burdens and negatively influences economic growth accordingly. All in all, it possesses great significance to continuously decrease renewable energy deployment costs.

As for the estimated results of the control variables, the elastic coefficients of capital investment and openness are both significantly positive, which shows capital investment and openness make significant contributions to promoting EG. In the context of the Belt and Road Initiative, trade exchanges between countries are more frequent. The increase in trade and investment has significantly promoted the EG of various countries. In contrast, the elasticity coefficient of energy intensity is significantly negative, implying energy intensity (i.e., energy use per unit of GDP) negatively affects EG. This is because the current economic growth is technology-oriented rather than labor-intensive. The advancement of technology contributes to increasing energy utilization efficiency. Per unit of energy consumption can lead to greater economic output, thereby contributing to promoting economic growth. As for the labor, its elasticity coefficient is not significant, showing that the increase in the
number of labor force is not effective in driving economic growth. This is because of the transformation and upgrading of the industrial structure, the demand for high-quality labor in industrial development is increasing. Apart from labor-intensive industries, the contributions of technology-intensive and capital-intensive industries to economic growth are increasing.

Since economic growth is a dynamic process, the static panel model cannot capture its lagged effect. The dynamic panel estimated results are reported in Models (3)-(6). Model (3) and model (5) present the estimation results through the difference-GMM method. Model (4) and Model (6) present the estimation results through the system-GMM method. From the results of Arellano-Bond test, AR(3) and (4) statistics are not significant, indicating that the disturbance term has a low-order moving average process. The Sargan test results indicate that all instrumental variables are valid. Therefore, the GMM methods used in this paper are appropriate (Windmeijer 2005).

As shown in Table 5, Model (3) and Model (4) include five variables, while all variables are considered in Model (5) and Model (6) estimated by difference-GMM and system-GMM respectively. It can be seen from Models (3)-(6), the elastic coefficient of the lagged lnEG is significantly positive, showing that the previous EG level is positively correlated with the current economic growth level. Economic growth is a continuous and cumulative adjustment process with significant lagged effects. This finding proves the effectiveness of the dynamic panel model to some extent. Additionally, the coefficient sign of the core explanatory variable is the same in Models (3)-(6), there exists a significant inverted U-shaped nexus between SREC and EG. In addition, all dynamic models also confirm that the effect of openness on EG is negative; in contrast, the influences of capital, labor, and energy intensity are not significant. Overall, in static and dynamic models, the coefficients magnitudes show significant differences.

Results and discussion of the SREC-CEI model

The previous section has explored the SREC-EG nexus and obtained some meaningful findings. Similarly, according to the research ideas of the theoretical methodology, this paper establishes both static and dynamic panel models to reveal how
renewable energy development affects CEI. The regression results are listed in Table 6. Model (7) and (8) present the estimated results of the static model through the 2SLS method. Models (9)-(12) show the estimation results of the dynamic model through difference-GMM and system-GMM approaches. Based on panel Granger causality test in Table 4, EG and CEI, and SREC and CEI all display bidirectional causalities. Therefore, SREC and economic growth are treated as endogenous variables in the SREC-CEI model. This paper adopts three estimation strategies: 2SLS, difference-GMM and system-GMM methods, thereby solving the endogeneity problems. As presented in Table 6, the $R^2$ reported in Model (7) and Model (8) is at least 92%, indicating that the models fit well.

**Table 6**

Regression results of the SREC-CEI model.

| Variables | Model (7) 2SLS | Model (8) 2SLS | Model (9) Diff-GMM | Model (10) Sys-GMM | Model (11) Diff-GMM | Model (12) Sys-GMM |
|-----------|----------------|----------------|--------------------|--------------------|--------------------|--------------------|
| L.InCEI   | 0.328***       | 0.494***       | 0.327***           | 0.507***           |
|           | (0.034)        | (0.043)        | (0.082)            | (0.087)            |
| lnSREC    | -0.026**       | -0.018***      | -0.044***          | -0.038***          | -0.046**           | -0.042***          |
|           | (0.010)        | (0.011)        | (0.015)            | (0.013)            | (0.020)            | (0.015)            |
| lnEI      | 0.919***       | 0.931***       | 0.680***           | 0.491***           | 0.742***           | 0.500***           |
|           | (0.024)        | (0.025)        | (0.031)            | (0.001)            | (0.096)            | (0.094)            |
| lnURB     | 0.069          | -0.045         | 0.334              | 0.795              |
|           | (0.060)        | (0.068)        | (0.848)            | (1.182)            |
| lnOPN     | 0.002          | 0.003          | 0.015              | -0.172             |
|           | (0.013)        | (0.013)        | (0.254)            | (0.030)            |
| lnEG      | 0.053*         | 0.432***       | 0.088              | -0.856             |
|           | (0.028)        | (0.112)        | (0.748)            | (1.400)            |
| (lnEG)^2  | -0.022***      | -0.004         | 0.046              |                   |
|           | (0.007)        |               | (0.041)            | (0.076)            |
| Int       | -0.005***      | -0.005***      | 0.0004             | -0.001             | -0.002             |
|           | (0.001)        | (0.001)        | (0.001)            | (0.004)            | (0.004)            |
| AR(1)     | -3.233***      | -3.559***      | -2.233**           | -2.660***          |
| AR(2)     | -1.356         | -1.359         | -1.085             | -0.979             |
| AR(3)     | -0.242         | 0.294          | -0.202             | 0.714              |
| AR(4)     | 0.699          | 0.730          | 0.821              | 1.061              |
| Sargan test | 22.459        | 22.240         | 19.358             | 21.694             |
| Wald chi2 | 16797.01**     | 23242.59**     | 18339.68**         | 13276.77**         |
|           | *              | *              | *                  |                   |
| $R^2$     | 0.9267         | 0.9283         |                    |                   |
Observation 504 504 476 504 476 504
Regional fixed effects ✓ ✓ ✓ ✓ ✓ ✓
Time fixed effects ✓ ✓ ✓ ✓ ✓ ✓

Note: (1) * represents p<0.10, ** represents p<0.05, *** represents p<0.01. (2) Standard errors are reported in brackets. (3) GMM estimations are obtained through the xtdpd command in the STATA software. (4) AR statistics are the results of Arellano-Bond test. (4) In GMM estimators, the predetermined variable is lnCEI_{i,t-1}, while the endogenous variables include lnSREC, lnEG and lnEG2.

Model (9) and Model (10) serve as a reference. It is found that whether the four variables are included doesn’t affect the coefficient sign of renewable energy development, which indicates no serious collinearity problem in regression analysis. As shown in Model (12), the elastic coefficient of the first-order lagged term of lnCEI is significantly positive, indicating CEI in the previous period positively affects the CEI at the present period, that is, carbon emissions are characterized as a continuous and cumulative process with significant lagged effects (Huang et al. 2019). It further confirms the necessity of establishing a dynamic panel model. The elasticity coefficients of SREC are significantly negative in Models (7)-(12), implying renewable energy is beneficial to decreasing CEI. Environmental degradation such as climate change and air pollution caused by fossil energy combustion has prompted various countries aware of the importance of lessening fossil fuel consumption and facilitating renewable energy deployment. As the renewable energy deployment scale expands, its role in reducing carbon emissions will gradually become prominent.

The elasticity coefficient of economic growth is significantly positive, while its quadratic term is significantly negative; however, in Model (11) and Model (12), the estimated coefficients are not significant. That implies a non-linear inverted U-shaped nexus between CEI and EG. Only when the economic development level reaches a certain level will it make a significant contribution to reducing carbon emission intensity. This finding verifies the EKC theory and is supported by lots of previous studies (Baladonaves et al., 2018; Dong et al., 2018b). In the initial stage, industrial economic development requires a large number of energy inputs, causing lots of carbon
emissions. With the improvement of technology and the upgrading of economic structure and energy consumption structure, economic growth generally contributes to decreasing carbon emission intensity.

As for other control variables, their impacts on CEI display visible differences. The influence of energy intensity is significantly positive, showing technical progress plays an important role in increasing CEI. According to Model (8), for every 1% increase in energy intensity, CEI will increase by 0.931%. Previous studies have shown improving energy efficiency is imperative for reducing carbon emissions (Han et al. 208; Fan et al. 2019). Therefore, it is necessary to develop energy-saving and emissions reduction technologies. Besides, the elasticity coefficients of openness are either positive or negative, but they are not statistically significant, indicating the impact of openness on CEI is uncertain. On the one hand, the technology spillover effect is beneficial to carbon emissions; on the other hand, the embodied carbon emission from trade and the entry of high-polluting companies may hinder domestic carbon emissions reduction. In addition, the results show that urbanization hinders the reduction of CEI in most models, but its impact is not statistically significant. This is because urbanization has dual impacts on carbon emissions. On the one hand, the process of urbanization has promoted production and living activities, resulting in increased pressure on resources and environment. On the other hand, population agglomeration and compact development promote the intensive use of resources, thereby contributing to carbon emission reduction.

Analysis of the spatial differences of EG and CEI

In this paper, the inequalities in EG and CEI are evaluated by the Gini coefficient. The changes in the inequalities indexes during 1999-2017 are shown in Fig. 3. As shown in Fig. 3, over the period 199-2017, the Gini coefficient of CEI is significantly larger than the Gini coefficient of EG, indicating the regional inequality in CEI is significantly larger than the regional inequality in EG. It is clear that the two inequality indicators show a clear downward trend. It is because the BRI countries have strengthened regional economic and emission reduction cooperation. For economic growth, the inequality decreases from 0.51 in 1999 to 0.46 in 2017, with a decline rate
of 10.8%. For carbon emission intensity, the inequality decreases from 0.42 in 1999 to 0.31 in 2017, with a decline rate of 26.6%. This shows that the BRI countries tend to achieve coordinated low-carbon sustainable development over time. The reasons for the cross-country inequalities of EG and CEI will be investigated in the following sections.

**Fig. 3** The changes of the inequalities in EG and CEI among the BRI countries during 1999-2017

**Shapley value decomposition results of EG**

In order to reveal the mechanism behind the regional inequality of EG, this study applies the regression-based Shapley decomposition to decompose the overall inequality of EG into different factors. Based on the regression equation of Model (1) in Table 5, this paper quantifies the impacts of the five influencing factors (including the share of renewable energy, energy intensity, capital, labor, and openness) on EG inequality through Shapley value decomposition. As the Shapley decomposition is conducted by year, the time trend term (i.e., time non-observed effect) has no contribution to the EG inequality. On average, the five factors in the SREC-EG model together can explain 70% of the overall inequality of EG during 1999-2017. The contribution values of these factors to the economic growth gap are shown in Fig 4.
Furthermore, this paper compares the contribution rates of different factors (see Fig. 5). As shown in Fig. 4 and Fig. 5, the contributions of all factors are positive, indicating that the spatial distribution of individual factors contributes to the spatial heterogeneity in economic growth. On the whole, the inequality in EG is primarily due to the regional differences in capital investment, followed by energy intensity and renewable energy consumption. By contrast, the impacts of labor and openness are negligible.

It is found that, in every single year, capital is the most critical factor influencing the regional disparities of EG, with an average contribution rate of 81.54% during 1999-2017; it indicates the regional inequality of capital accounts for most of the inequality of EG among the BRI countries. This finding is reasonable because developed countries have bigger capital investment compared with less developed countries. This means that economic growth is mainly driven by capital investment. Specially, the contribution value of capital increases from 0.26 in 1999 to 0.31 in 2017, suggesting its impact on economic growth is increasing. Also, Fig. 4 shows that energy intensity is also crucial in explaining the cross-country inequality in economic growth, and its contribution is relatively stable over the study period. It indicates the technological gap between countries has an essential impact on shaping the economic gap. It is self-evident that developed countries have high levels of technologies, compared with less developed countries. As for the SREC, it plays a minor role in affecting the economic growth gap among the BRI countries, with an average contribution rate of 4.2% during 1999-2017. That implies renewable energy has a limited influence on economic growth from the spatial perspective. However, compared with other factors, openness degree and labor have little impact on influencing the economic growth gap.
**Fig. 4** Shapley value decomposition results for EG

**Fig. 5** Contribution rates of the five factors

**Shapley value decomposition results of CEI**

Based on the regression equation of Model (7) in Table 6, Shapley value
decomposition is utilized to decompose the cross-country inequality of CEI in the BRI. The total contribution of the determinants to the overall Gini coefficient is at least 87.2%, indicating the explained proportion of CEI inequality exceeds 87.2% through the Shapley decomposition. On average, the individual factors in the SREC-CEI model together can explain as high as 88.82% of the overall inequality of CEI during 1999-2017, while the contribution of the residual is quite small. The Shapley decomposition is adequate to reveal the reasons for the spatial heterogeneity of CEI among the BRI countries.

Fig. 6 and Fig. 7 present the contribution values and contribution ratios of different factors to the CEI inequality, respectively. Through the Shapley decomposition, the gaps of CEI among the BRI countries are attributed to the regional inequalities of SREC, EI, EG, OPN, and URB. It is found that the contributions of all factors are positive, indicating that the spatial distribution of individual factors contributes to the spatial heterogeneity in economic growth. To be more specific, the greatest contribution is reported by EI, followed by SREC, UR, and EG, while the contribution of OPN is negligible.

As shown in Fig. 7, the average contribution rate of EI is as high as 92.4% during 1999-2017. The spatial inequality of CEI among the BRI countries is mostly caused by the spatial inequality of energy intensity. The previous regression analysis has found that energy intensity positively affects CEI. Moreover, countries with lower CEI usually have higher technological levels and lower energy intensity, thereby increasing the cross-country inequality in CEI. This finding implies the great significance of technological improvement in carbon reduction for the BRI countries. Specially, the impact of EI displays a significant downtrend over time. The contribution values of EG, UR, and SREC are quite close. During 1999-2017, the average contribution rate of SREC is 2.4%, indicating the impact of SREC is relatively small so far from the spatial perspective. Similarly, the average contribution rates of UR and EG are 2.24% and 2.84%, respectively. In addition, with an average contribution rate of 0.07%, openness degree has very little influence on the cross-country CEI inequality, compared with other factors. This is reasonable since the regression analysis also suggests that
openness does not significantly influence CEI.

**Fig. 6** Shapley value decomposition results for CEI

**Fig. 7** Contribution rates of the five factors

**Conclusions and policy implications**

As the BRI countries have witnessed extensive renewable energy development and cooperation, this study aims to uncover whether renewable energy development can help achieve economic growth and CO$_2$ intensity reduction simultaneously. Compared with previous literature, the estimation results of this study are more robust and reliable.
The following is the main results. (1) There are bidirectional Granger causalities between SREC, EG, and CEI. This shows that there is a systematic connection between the three variables. When empirically studying how renewable energy development affects EG and CEI, it is essential to consider and solve the endogeneity problems in the econometric model. (2) All models demonstrate the inverted U-shaped nexus between SREC and economic growth, indicating renewable energy deployment costs are urgent to be decreased with the increase in SREG. Besides, capital investment, openness, and labor positively affect economic growth, while energy intensity negatively affects economic growth. From the spatial heterogeneity perspective, the inequality in economic growth is primarily due to the regional gap of capital investment, followed by energy intensity and renewable energy consumption. By contrast, the impacts of labor and openness are negligible. (3) Renewable energy contributes to reducing CEI. Besides, an inverted U-shaped nexus between economic growth and CEI is observed. Energy intensity positively affects CEI, while the impacts of urbanization and openness are insignificant. From the spatial heterogeneity perspective, the cross-country CEI inequality is principally caused by the gap of energy intensity, followed by SREC, urbanization, and economic growth, while the contribution of the openness gap is little.

On the basis of the above conclusions, this study presents several important policy implications.

First, renewable energy development requires lowering the dependence on fossil energy. However, this process requires gradual and orderly advancement, and a comprehensive tradeoff between economic costs and energy transition. Local governments must vigorously encourage the market to absorb renewable energy and avoid excessive dependence on capital investment. As the renewable energy scale expands, it is necessary to take more measures to maintain its stable and sustainable development, such as market-oriented transactions, and exemption of technology and equipment import tariffs. More importantly, there is a need to reduce energy use costs through technological innovation.

Second, the realization of low-carbon economic growth still mainly depends on
technological progress and innovation. Specifically, it is necessary to promote the absorption and innovation of technology, increase R&D investment, and propel innovation-driven economic growth. It is imperative to improve energy utilization efficiency as reflected in decreasing energy use needed for generating per unit economic output. In detail, the service industry-based tertiary industry has low energy consumption and minor pollution. It is indispensable to promote the economic structure transformation, change the economic growth momentum, and vigorously promote the tertiary industry. Furthermore, the transition from fossil energy to clean energy is conducive to reducing energy intensity, and will also have a profound impact on the global industrial chain.

Third, the BRI countries should expand the degree the openness, strengthen trade exchanges between countries along the BRI, lower tariff levels, and eliminate trade barriers. Specially, it is of great importance to introduce technology-intensive capital and take advantage of the spillover effects of FDI, thereby promoting the management and technological levels of host country enterprises. In addition, the BRI countries should extensively carry out international cooperation in the field of green and renewable energy. Although the BRI countries have broad prospects for the development of renewable energy, most countries are also facing a shortage of funds. The BRI countries should open up financial markets. More importantly, financial institutions such as Asian Infrastructure Investment Bank and New Development Bank should actively invest in the BRI renewable energy projects. Besides, there is a need to provide green financial services for the BRI countries, establish funds to support green infrastructure construction, and build a local green financial mechanism.

Fourth, there is a need to adjust the development notion of urbanization. The traditional urbanization process is characterized by land urbanization centered on urban area expansion, thereby causing huge resources and environmental costs. Therefore, the urbanization process should emphasize the flows of production factors such as human, capital, and techniques to cities. Specifically, in the future urbanization process, it has great meaning to emphasize the agglomeration effect of the urban economy, such as strengthening public facilities and infrastructure construction, enhancing capital
intensity and technology intensification, and promoting the intensive use of resources.

Given data availability, this paper covers a limited number of countries. The sample is expected to be extended, and the future research can even cover the global scope. Several future research directions deserve our attention. In addition to the economic or environmental impacts of renewable energy, renewable energy policy design deserve in-depth studies. There is a need to study the driving mechanisms of renewable energy penetration and explore the deployment potential of renewable energy technologies in the BRI. To be more specific, the impacts of related policies should attract sufficient research attention, such as financial policies, environmental policies, and investment policies. Especially, it is of great importance to quantify the impact of trade on renewable energy deployment in the BRI countries and strengthen regional energy cooperation. What’s more, given the international environment has undergone profound changes in recent years, it is necessary to reveal the phase characteristics of renewable energy development along the Belt and Road.

**Ethical Approval**

Not applicable

**Consent to Publish**

Not applicable

**Consent to Participate**

Not applicable

**Competing Interests**

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

**Availability of data and materials**

The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

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Authors Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Jianhan He], [Hengming Peng] and [Hailin Duan]. Funding acquisition: [Hengming Peng, Hailin Duan]. Supervision: [Jianhua Chen]. The first draft of the manuscript was written by [Jianhan He.] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

Akadiri SS, Alola AA, Akadiri AC, Alola UV (2019) Renewable energy consumption in EU-28 countries: Policy toward pollution mitigation and economic sustainability. Energ Policy 132:803-810

Almulali U, Sab CNBC (2012) The impact of energy consumption and CO2 emission on the economic growth and financial development in the Sub Saharan African countries. Energy 39(1):180-186

Apergis N, Payne JE (2010) Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. Energ Policy 38(1):656-660

Apergis N, Payne JE, Menyah K, Wolderufael Y (2010) On the causal dynamics between emissions, nuclear energy, renewable energy, and economic growth. Ecol Econ 69(11):2255-2260

Arellano M, Bond S (1991) Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations. The Review of Economic Studies 58(2): 277-297

Arent DJ, Wise A, Gelman R (2011) The status and prospects of renewable energy for combating global warming. Energ Econ 33(4):584-593

Baladonaves R, Banospino J, Mayor M, et al (2018) Do countries influence neighbouring pollution? A spatial analysis of the EKC for CO2 emissions. Energy Policy 123: 266-279.

Bento JPC, Moutinho V (2016) CO2 emissions, non-renewable and renewable electricity production, economic growth, and international trade in Italy. Renew Sust Energ Rev 55:142-155

Blundell R, Bond S (1998) Initial conditions and moment restrictions in dynamic panel data models. J Econometrics 87(1):115-143

Bond SR, Hoeffler A, Temple J (2001) GMM estimation of empirical growth models. Available at SSRN: https://ssrn.com/abstract=290522

BP 2019. British petroleum statistical review of world energy. Available at: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (Accessed 25 July 2020)

China New Energy International Alliance (CNEIA) (2019) Research on the Belt and Road Initiative renewable energy development cooperation path and promotion mechanism

Dell M, Jones BF, Olken BA (2012) Temperature Shocks and Economic Growth: Evidence from the Last Half Century. Am Econ J-Macroecon 4(3):66-95

Destek MA, Aslan A (2020) Disaggregated renewable energy consumption and environmental pollution nexus in G-
7 countries. Renew Energ 151:1298-1306

Dietz T, Rosa EA (1997) Effects of population and affluence on CO₂ emissions. Proceedings of the National Academy of Sciences of the United States of America 94(1):175-179

Dogan E, Altinoz B, Madaleno M, Taskin D (2020) The impact of renewable energy consumption to economic growth: A replication and extension of Inglesi-Lotz (2016). Energ Econ 90 104866

Dogan E, Seker F (2016) Determinants of CO₂ emissions in the European Union: The role of renewable and non-renewable energy. Renew Energ 94:429-439

Dong F, Bian Z, Yu B, Wang Y, Zhang S, Li J, Su B, Long R (2018a) Can land urbanization help to achieve CO₂ intensity reduction target or hinder it? Evidence from China. Resour Conserv Recy 13: 206-215

Dong F, Yu B, Hadachin T, Dai Y, Wang Y, Zhang S, Long R (2018b). Drivers of carbon emission intensity change in China. Resour Conserv Recyc 129: 187-201

Dumitrescu EI, Hurlin C (2012) Testing for Granger non-causality in heterogeneous panels. Econ Model 29(4):1450-1460

European Commission (2018) 2030 climate & energy framework. Brussels. https://ec.europa.eu/clima/policies/strategies/2030. (Accessed 7 August 2020)

Fan J, Da Y, et al. (2019) Determinants of carbon emissions in ‘Belt and Road initiative’ countries: a production technology perspective. Applied Energy 239: 268-279

Fan W, Hao Y (2020) An empirical research on the relationship amongst renewable energy consumption, economic growth and foreign direct investment in China. Renewable Energy 146: 598-609.

Granger CWJ (1969) Investigating causal relations by econometric models and cross-spectral methods. Econometrica 37:424-438

Han L, Han B, Shi X, Su B, et al. (2018) Energy efficiency convergence across countries in the context of China's Belt and Road initiative. Applied Energy 213: 112-122.

Huang J, Liu C, Chen S, Huang X, Hao Y (2019) The convergence characteristics of China's carbon intensity: Evidence from a dynamic spatial panel approach. Sci Total Environ 668:685-695

Irandoust M (2016) The renewable energy-growth nexus with carbon emissions and technological innovation: Evidence from the Nordic countries. Ecol Indic 69:118-125

Jebli MB, Youssef SB, Ozturk I (2016) Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries. Ecol Indic 60:824-831

Jenniches S (2018) Assessing the regional economic impacts of renewable energy sources – A literature review. Renew Sust Energ Rev 93:35-51

Jiang B, Sun Z, Liu M (2010) China's energy development strategy under the low-carbon economy. Energy 35(11):4257-4264

Jing S, Leng Z, Cheng J, Shi Z (2020) China's renewable energy trade potential in the" Belt-and-Road" countries: A gravity model analysis. Renew Energ 161:1025-1035

Kahia M, Aissa MSB, Charfeddine L (2016) Impact of renewable and non-renewable energy consumption on economic growth: New evidence from the MENA Net Oil Exporting Countries (NOECs). Energy 116:102-115.

Khan SAR, Zhang Y, Kumar A, Zavadskas EK, Streimikiene D (2020) Measuring the impact of renewable energy, public health expenditure, logistics, and environmental performance on sustainable economic growth. Sustain Dev
Liu Y, Hao Y (2018) The dynamic links between CO₂ emissions, energy consumption and economic development in the countries along "the Belt and Road". Science of the total Environment 645: 674-683.

Lund H (2007) Renewable energy strategies for sustainable development. Energy 32(6):912-919

Mahmud MAP, Huda N, Farjana SH, Lang C (2020) Life-cycle impact assessment of renewable electricity generation systems in the United States. Renew Energ 151:1028-1045

Maji IK, Sulaiman C, Abdulrahim AS (2019) Renewable energy consumption and economic growth nexus: A fresh evidence from West Africa. Energy Rep 5:384-392

Marques AC, Fuinhas JA, Manso JRP (2010) Motivations driving renewable energy in European countries: A panel data approach. Energ Policy 38(11):6877-6885

Mbarek MB, Saidi K, Feki R (2018) How Effective Are Renewable Energy in Addition of Economic Growth and Curbing CO₂ Emissions in the Long Run? A Panel Data Analysis for Four Mediterranean Countries. Journal of The Knowledge Economy 9(3):754-766

Menegaki AN (2011) Growth and renewable energy in Europe: A random effect model with evidence for neutrality hypothesis. Energ Econ 33(2):257-263

Menyah K, Wolderufael Y (2010) CO₂ emissions, nuclear energy, renewable energy and economic growth in the US. Energy Policy 38(6):2911-2915

Nathaniel S, Khan SAR (2020) The Nexus between Urbanization, Renewable Energy, Trade, and Ecological Footprint in ASEAN Countries. J Clean Prod 272 122709

NDRC (National development and reform commission) People's Republic of China. Enhanced actions on climate change: China's intended nationally determined contributions. Beijing; 2015 [in Chinese]

Ocal O, Aslan A (2013) Renewable energy consumption-economic growth nexus in Turkey. Renew Sust Energ Rev 28:494-499

Qi S, Peng H, Zhang X, Tan X (2019) Is energy efficiency of Belt and Road Initiative countries catching up or falling behind? Evidence from a panel quantile regression approach. Appl Energ 253:113581

Rahman MM, Velayutham E (2020) Renewable and non-renewable energy consumption-economic growth nexus: New evidence from South Asia. Renew Energ 14:399-408

Rauf A, Liu X, Amin W, Ozturk I, Rehman O, Hafeez M (2018a) Testing EKC hypothesis with energy and sustainable development challenges: a fresh evidence from belt and road initiative economies. Environmental Science and Pollution Research 25(32): 32066-32080.

Rauf A, Liu X, Amin W, Ozturk I, Rehman O, Sarwar S (2018b) Energy and ecological sustainability: Challenges and panoramas in belt and road initiative countries. Sustainability 10(8):2743.

Sharif A, Baristuzemen O, Uzuner G, Ozturk I, Sinha A (2020) Revisiting the role of renewable and non-renewable
energy consumption on Turkey’s ecological footprint: Evidence from Quantile ARDL approach. Sustain Cities Soc 102138
Sharif A, Raza S, Ozturk I, Afshan S (2019) The dynamic relationship of renewable and nonrenewable energy consumption with carbon emission: a global study with the application of heterogeneous panel estimations. Renewable Energy 133:685-691.
Sharrocks, A.F. Decomposition procedures for distributional analysis: a unified framework based on the Shapley value. J. Econ. Inequal. 1999, 11, 99-126.
Solow RM (1957) Technical Change and the Aggregate Production Function. The Review of Economics and Statistics 39(3):312-320
Tahvonen O (1997) Fossil Fuels, Stock Externalities, and Backstop Technology. Canadian Journal of Economics 30(4):855-874
UNFCCC (1992) United Nations Framework Convention on Climate Change United Nations
UNFCCC (2015) Paris agreement, decision 1/CP.17. In: United Nations Framework Climate Change Convention. Paris
Wan, G. Regression-based inequality decomposition: Pitfalls and a solution procedure. WIDER Discussion Papers/World Institute for Development Economics (UNU-WIDER) 2002.
Wang B, Wang Q, Wei Y, Li Z (2018) Role of renewable energy in China’s energy security and climate change mitigation: An index decomposition analysis. Renew Sust Energ Rev 90:187-194
Wang Q, Wang L (2020) Renewable energy consumption and economic growth in OECD countries: A nonlinear panel data analysis. Energy 207 118200
Wang R, Mirza N, Vashieva, DG, Abbas Q, Xiong D (2020) The nexus of carbon emissions, financial development, renewable energy consumption, and technological innovation: What should be the priorities in light of COP 21 Agreements? J Environ Manage 271 111027
Windmeijer F (2005) A finite sample correction for the variance of linear efficient two-step GMM estimators. J Econometrics 126(1):25-51
World Bank (2019) World development indicators. Washington, DC: World Bank
Xie Y, Dai H, Dong H (2018) Impacts of SO2 taxations and renewable energy development on CO2, NOx and SO2 emissions in Jing-Jin-Ji region. J Clean Prod 171:1386-1395
Yao L, Andrews-Speed P, Shi X (2019) Asean Electricity Market Integration: How can belt and road initiative bring new life to it? The Singapore Economic Review 1950041.
Yao S, Zhang S, Zhang X (2019) Renewable energy, carbon emission and economic growth: A revised environmental Kuznets Curve perspective. J Clean Prod 235:1338-1352