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Is energy efficiency of Belt and Road Initiative countries catching up or falling behind? Evidence from a panel quantile regression approach

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HIGHLIGHTS

- Convergence in energy efficiency of BRI counties and its factors are studied.
- Energy efficiency along BRI experienced an increasing trend except 2009 and 2010.
- BRI countries with low TFEE are catching up with countries with high TFEE.
- High-income & Eastern Europe and West Asia countries have faster catch-up rate.

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ABSTRACT

The Belt and Road Initiative (BRI) has raised concern that it may involve an extensive economic growth pattern at a higher cost of energy and the environment, and China is making a great effort to construct a green BRI, which may improve the general energy efficiency of BRI countries. Therefore, it is important to investigate whether backward countries with low energy efficiency are catching up with frontier countries or falling behind. In response, this paper adopts DEA to calculate the total-factor energy efficiency (TFEE) of the BRI countries, and investigates heterogeneous beta-convergence in energy efficiency of BRI counties and its factors. The results indicate that: (1) except for 2009 and 2010, the TFEE along the BRI experienced an increasing trend due to the global finance crisis; (2) BRI countries with low TFEE are catching up with countries with high TFEE, and more significantly when the TFEE growth rate is greater; (3) the TFEE converges at a faster rate in high-income BRI countries and Eastern Europe and West Asia countries; and (4) inadequate innovation ability and a weak R&D absorption capacity may decelerate the energy efficiency convergence rate of BRI countries, especially those with low-income.

1. Introduction

China initiated its 2013 *Silk Road Economic Belt and 21st Century Maritime Silk Road* policy, i.e., Belt and Road Initiative (BRI), to strengthen economic prosperity and regional cooperation. Endorsed by all member States of the United Nations in 2015, *Transforming Our World: the 2030 Agenda for Sustainable Development* sets 17 ambitious sustainable development goals (SDGs) in three dimensions, namely, economic development through good governance, social inclusion, and environmental sustainability[1]. The BRI represents a commitment to promoting globalization in a more open, inclusive, balanced and sustainable way, to help achieve the SDGs [1]. As important SDG goals are of vital interest to countries along the BRI, combating climate change along the BRI is closely related to building a community of a shared future for humankind [2].

The BRI covers 65 countries, most of which have lower-middle-income economies[2] - comprising 62% of the global population [3]. However, as shown in Fig. 1, the BRI has contributed less than 30% of global GDP in recent years, with a share of almost 50% of the world's primary energy consumption. Moreover, their energy consumption,

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[1] http://www.fmprc.gov.cn/web/ziliao_674904/zt_674979/dnzt_674981/qtzt/2030kcxfzyc_686343/P020170824650025885740.pdf.
[2] https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.

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carbon emissions per unit GDP are 50% more than the global average, with steel consumption, cement consumption, and water consumption per unit GDP being twice as much as the global average[3]. It seems that countries along the BRI have an extensive economic growth pattern at a much higher cost to the environment and resources. There are great differences in energy efficiency despite the general low energy efficiency of the countries involved [4], raising the question of whether the BRI will accelerate global energy consumption and deteriorate the global ecological environment [5,6].

Under such a background, how to coordinate the relationship between socio-economic development and greenhouse gas emissions for BRI countries has become an important research topic [7]. It is believed that the environmental challenge can be met by increasing energy efficiency [8], and China is taking ecological and environmental protection very seriously in BRI cooperation. It is making a great effort to construct a green BRI by promoting international production capacity cooperation, eco-friendly infrastructure construction, and sustainable production and consumption, boosting green trade, and increasing support for green financing to enhance financial integration[4]. A green BRI would improve general energy efficiency and promote the environmental issues connected with the BRI. As the general energy efficiency of BRI countries is lagging behind other countries, the BRI may help narrow the energy efficiency gap among BRI countries.

Therefore, it is important to investigate whether backward countries with low energy efficiency are catching up with the frontier countries or falling behind. More specifically, (1) What is the total-factor energy efficiency (TFEE) of BRI countries and is it increasing or decreasing? (2) Are the TFEE of BRI countries converging to that of frontier countries or to the benchmark EU? As a highly developed economy and major contributor to promoting global climate change mitigation, European Union countries have much higher energy efficiency than the BRI countries and can be considered as a benchmark. (3) Due to the different economic development stages and geographical location, the TFEE con/divergence of BRI countries may be also different, so what is the difference in the TFEE con/divergence rate for different groups? (4) Most importantly, if the TFEE of BRI countries does con/diverge, what are the influencing factors involved?

Driven by these motivations, the main contents of this paper are as follows. (1) The 1995–2015 TFEE of the 60 BRI countries is firstly established using data envelopment analysis (DEA). It should be noted that such traditional energy efficiency indicators as energy intensity (energy input per GDP) consider energy as the only input to create GDP, and omit such other essential inputs as capital and labor [9]. In contrast, a multiple factor model for assessing energy efficiency will be more beneficial than such partial indicators [10]. (2) We investigate whether TFEE converges or diverges within BRI countries, and between BRI countries and 15 developed European Union countries by panel quantile regression to provide a complete description of the conditional distribution involved. (3) Given the heterogeneity of the TFEE convergence rate within BRI countries with different characteristics, we further divide the 60 BRI countries into two groups by development level and geographical location. Then we analyze the TFEE convergence and growth changes of these two groups. (4) The main factors are identified that may influence the TFEE con/divergence rate of BRI countries.

The paper makes a three-fold contribution. (1) We explore the TFEE convergence of 60 BRI countries, using 15 ‘frontier’ EU countries (EU-15) as a benchmark to study whether the BRI countries’ TFEE is catching up with the EU-15. (2) We provide a complete picture of TFEE con/divergence to answer not only whether TFEE con/diverges but also the heterogeneous con/divergence rates with different TFEE growth rates between the 60 BRI countries, and between the 60 BRI countries and EU-15 by panel quantile regression. (3) The main economic factors (income, urbanization rate), structural factors (industry structure, energy structure), and technology factors (trade, FDI, R&D) are investigated for their influence on the TFEE convergence of BRI countries.

The remainder of this paper is structured as follows: Section 2 reviews the convergence analysis literature in the field of energy economics; Section 3 analyzes the mechanism through which the energy efficiency of BRI countries can catch up; Section 4 presents the methods used and data description; Sections 5 and 6 provide the empirical results and associated discussion, while Section 7 concludes the paper by identifying the important policy implications arising from the work.

2. Literature review

Convergence is referred to as income in poor countries catching-up with that of rich countries [11]. There are two main concepts of convergence in the growth literature, i.e., β-convergence and σ-convergence [12]. β-convergence refers to a negative relationship between the growth rate of income and its initial level, which implies that disadvantaged economics grow faster and catch up [13].σ-convergence examines whether the dispersion of income for a group of countries decreases over time [14]. Convergence has recently been expanded to the field of energy economics, with studies concentrating on the convergence of energy intensity, energy consumption, and carbon emissions [15,16].

A group of studies explores convergence in *energy intensity*, covering samples of countries or sectors. For example, Burnett and Madariaga’s [17] empirical analysis uses a two-step GMM model to show that energy intensity is converging for the 50 U.S. states examined; Mulder and Groot [18] evaluate 1970–2005 energy intensity development across 18 OECD countries and 50 sectors and analyze its β-convergence to reveal that backward countries are catching-up with frontier countries across sectors, with average rates of convergence higher in the services than manufacturing industries; while, conversely, Kounetas [19] finds the hypothesis of convergence patterns in energy intensity to be untenable in 23 European countries from 1970 to 2010.

Another group of studies examines the convergence in *energy consumption* per capita, including coal, electricity, and renewable energy. Mishra and Smyth’s [20] panel KPSS stationarity and Lagrange multiplier (LM) unit root tests with structural breaks, for example, provide support for convergence in energy consumption per capita of ASEAN countries over the period 1971 to 2011; Herrerias et al.’s [21] club convergence analysis confirms that residential electricity and coal consumption per capita in rural and urban areas converge to different steady-states; while Payne et al.’s [22] LM and RALS-LM unit root tests with endogenously-determined structural breaks provide clear support for stochastic convergence of per capita renewable energy consumption for the majority of U.S. states.

The third batch of literature examines convergence in *carbon emissions* per capita, obtaining inconsistent results, with Apergis and Payne [23], for instance, examining 50 U.S. states using the Phillips-Sul club convergence approach for the period 1980 to 2013, finding multiple convergence clubs both aggregated, by sector (residential, commercial, industrial, transport, and electric power), and for two of the three fossil fuel sources (natural gas and coal), with full panel club convergence in the case of petroleum; Churchill et al.’s [24] investigation across 44 developed and developing countries dating back to the beginning of the 20th century with the Residual Augmented Least Squares-Lagrange Multiplier (RALS-LM) unit root test, finds divergence prior to World War II and convergence over the post- World War II period in per capita CO_2 emissions; while Panopoulou and Pantelidis [25] disclose convergence in per capita CO_2 emissions among 128 countries in the early period of 1960–2003, although there seems to be two separate convergence clubs that converge to different steady states in recent years.

[3] http://www.cma.gov.cn/2011xzt/2015zt/20151127/2015112708/201511/t20151127_298400.html.

[4] https://www.yidaiyilu.gov.cn/wcm.files/upload/CMSydylgw/201705/201705080205025.pdf.

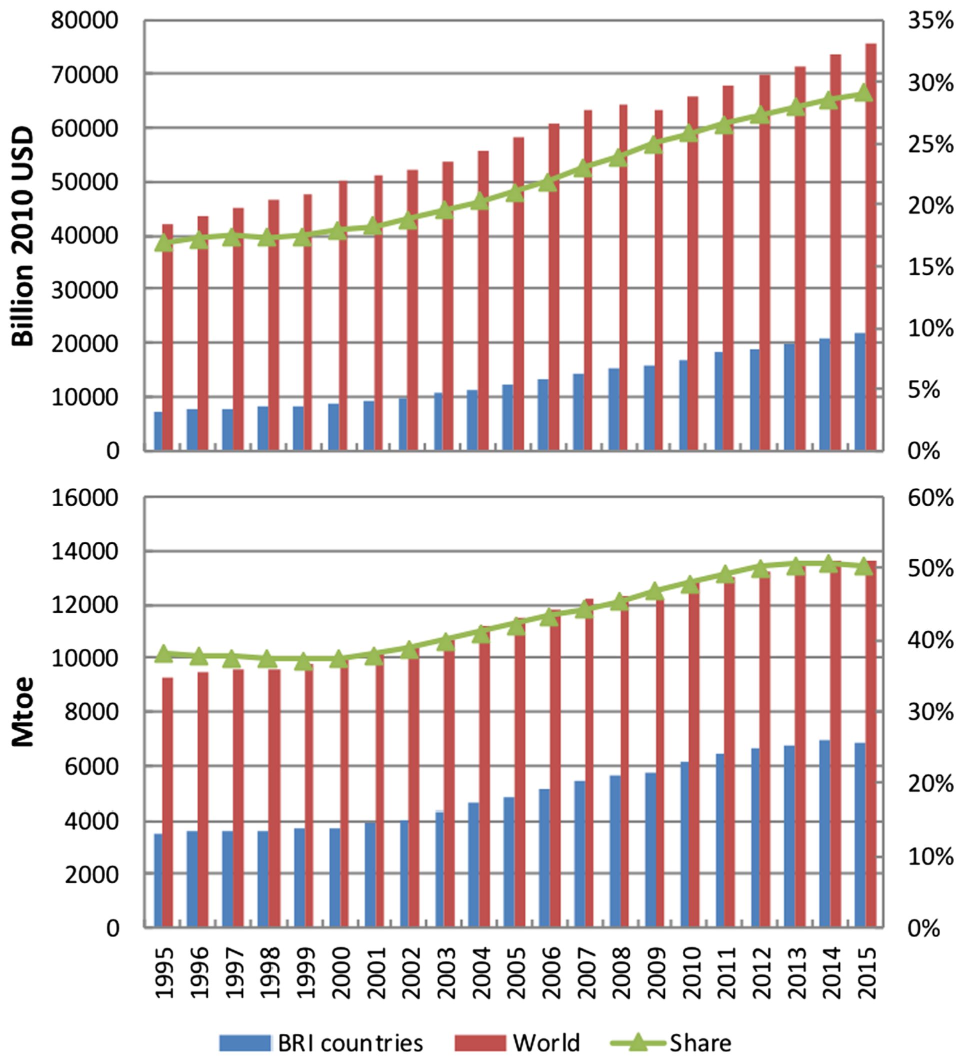

Fig. 1. Total GDP and primary energy consumption of the world and BRI countries, 1995–2015.

In addition, few previous studies have explored the factors that may accelerate or decelerate the convergence process in the field of energy economics and environment. Studies often concentrate only on whether it is converging rather than what expedites the convergence rate, by involving samples covering cooperative organizations, countries, and sectors, using time-series unit root, panel unit root, pair-wise unit root, stationarity tests, Phillips-Sul club convergence [26], distributional approach [27], and clustering algorithms [28]. However, the convergence process of energy efficiency is strongly related to a region's economic development stage, industrial structure, resource endowment, and technology level, especially in a developing economy [29]. Some countries produce more economic output with less energy input due to a cleaner production pattern, higher share of the tertiary industry in GDP, higher share of clean energy, and faster absorption or application to the diffusion of advanced technologies [30]. Consequently, the speed of energy efficiency convergence in these countries is faster than others. However, due to their comparative advantage in resources, or process of industrialization and urbanization, some countries have energy-intensive industries that have shifted from developed countries during the industrial upgrading, leading to a slow speed of energy efficiency convergence. Thus, it is important to recognize the key economic, structure, or technology factors that affect the energy efficiency convergence rate.

There are still some aspects to be improved, however. First, previous studies are mainly focused on the energy efficiency of the OECD, EU, United States, and China, for assessing convergence. Given the important role of BRI countries and possible contributions to tackling global climate change and sustainable development, this paper investigates not only whether the TFEE of BRI countries converges or diverges, but also the heterogeneous convergence rates in considering the inconsistent TFEE growth rates of BRI countries at different economic development stages, and within two BRI income level groups. Second, few previous studies have demonstrated the main factors that have a significant impact on accelerating or decelerating the energy efficiency convergence rate. In response, this paper examines the impact of economic indicators (economic development and urbanization), structure indicators (industry structure and energy structure), and technological indicators (R&D, FDI, and trade) on TFEE convergence.

3. Mechanism for energy efficiency catch-up

We analyze the mechanism through which energy efficiency may catch up with those in frontier BRI countries from the following three perspectives.

(1) Scale effect. Based on neo-classical growth theory, the income levels of poorer countries of the world are converging to those of richer countries. Following the assumption of diminishing returns, which implies higher marginal productivity of capital in a capital-poor country [31], poorer economies will therefore grow faster.

Thus there should be a negative correlation between the initial income level and the subsequent growth rate (β-convergence). Energy use is intrinsically linked with economic activity. Economic growth is expected to be the underlying channel for the catch-up phenomenon of energy efficiency/consumption.

First, the economic cooperation induced by the Belt and Road Initiative accelerates the economic growth of BRI countries to some extent. Economy-wide technological progress with economic development makes the fuel conversion process to useful work more efficient, and therefore the cost of useful energy tends to decline. The declining cost of products or service generates increased demand for useful work throughout the economy. Increased demand, in turn, requires bigger production units with greater economies of scale, further promoting energy efficiency improvement [32]. As backward countries with lower energy efficiency often have more rapid economic growth rate than frontier countries, the scale effect induces energy efficiency catch-up.

Second, energy efficiency convergence is thought to be related to income convergence owing to the inverted-U relationship between income and environmental performance [33]. The enhanced trade collaboration by the Belt and Road Initiative may promote income catch-up for backward countries. According to the EKC hypothesis, people increase their demand for a cleaner environment above a certain income level, which enforces the adoption of a series of stricter energy-saving and environmental regulations and measures to improve energy efficiency [34], thus improving energy use efficiency. Hence, the income-induced improvement of energy efficiency in backward developing countries may indirectly facilitate the energy efficiency catch-up process.

Third, economic development is accompanied by a rapid urbanization process, especially in developing countries, which can be facilitated by the Belt and Road Initiative through infrastructure construction and foreign investment. Urban dwellers with increasing income and enhancing awareness of energy saving may shift their consumption patterns towards green products [35]. In addition, the concentration of population and economic activity requires public transport services over long distances for transporting products, which decreases demand for individual transport [36]. In concentrating economic activities in the city, urbanization brings about economies of scale and the opportunity for energy efficiency catch-up.

(2) Structure effect. Shifting the economic structure and energy consumption structure is widely recognized as having the potential for improving energy efficiency. An economic structure shift from secondary industry to service industry is expected to increase energy efficiency. Secondary industry mainly includes mining and quarrying, electric power, natural gas, water production and supply, and manufacturing sectors, many of which are energy-intensive. However, the service industry is usually energy saving. An increased proportion of service industry will contribute to improving energy efficiency [37]. Changing the energy consumption structure from low efficiency solid fuels to higher efficiency gaseous and liquid fuel often facilitates energy efficiency improvement [38]. Considering the BRI cooperation in trade or energy may enable an economic and energy structure shift in backward countries so that energy efficiency catch-up may happen.
(3) Technology effect. Energy efficiency convergence can be the outcome of a technological catch-up, which largely determines energy efficiency. When the technology gap narrows, especially clean technology, lower energy efficiency countries will catch up with high-energy efficiency countries in the long term.

First, independent R&D induces technology innovation, which is the fundamental pathway to improving efficiency in the process of energy saving as it results in a reduction of environmental risk and other negative impacts of resources use (including energy use) with the production, or exploitation of a production process.

Second, the Belt and Road Initiative can result in closer international trade linkages, which allows foreign producers to transfer modern technologies to the host economy, especially in less developed countries, which may narrow the technology gap between the frontier and backward countries. The import of technology and equipment promotes energy productivity improvement by knowledge diffusion and technology spillover in a direct way. Exports make the returns of innovation activity increase, which in turn stimulates the innovation of the products and technologies of the host enterprises. In short, the absorption of technology spillovers brought by trade is expected to be beneficial in reducing the technology gap and energy efficiency gap.

Finally, the BRI enables more foreign investment among developed and backward BRI countries, from which technology from abroad can either be transferred through the market or transferred within the boundaries of the firm through the process of establishing a subsidiary through foreign investment. Thus, the technology or energy efficiency gap narrows, leading to the catch-up phenomenon of energy efficiency.

However, due to the difference in economic development stages, comparative advantages in natural resources, industrial and energy structure, and the abatement technology level of BRI countries, the convergence of energy efficiency may exhibit heterogeneity.

4. Methodology and data definition

4.1. TFEE calculated by DEA

Two methods are usually used to calculate TFEE. One is the parametric method represented by Stochastic Frontier Analysis (SFA), and the other is a non-parametric method represented by DEA. DEA is a method that identifies the production frontier to evaluate the relative efficiency of all decision-making units (DMUs) by linear programming. Typically using maximum likelihood estimation for regression, SFA allows single input (output) and multiple output (input) factors, while DEA allows multiple outputs and inputs with linear programming algorithm. In addition, SFA explicitly accommodates noise whereas DEA includes noise in the efficiency score rather than accounts for it directly. As for the functional form, SFA is specified (e.g., linear, semi-log, and double-log) while DEA's is not specified [39]. Here we adopt DEA as, compared with SFA, it does not involve assuming any particular functional form for the inputs and outputs, which avoids potential problems caused by assuming an inappropriate distribution of the error term [40].

As there are 10 EU BRI countries and we analyze the TFEE convergence of BRI countries relative to EU countries, the other 15 countries (EU-15) are used as benchmark countries. Thus, we calculate the TFEE of EU-15 and 60 BRI countries simultaneously in the same model. Assuming that every country is a $DMU_j (j = 1, 2, ..., 75)$, each DMU has m kinds of inputs and l kinds of outputs. Capita, labor, and energy are used as the inputs, and GDP as the output. The input-orientated Charnes-Cooper-Rhodes (CCR) model is used to evaluate relative efficiency under the assumption of constant returns to scale, with

$$min\left[\theta - \varepsilon\left(\sum_{r=1}^{l} s_r^+ + \sum_{i=1}^{m} s_i^-\right)\right]$$
$$s.\ t.\quad \begin{cases} \sum_{j=1}^{n} X_{ij}\lambda_j + s_i^- = \theta X_{ij0} \quad (i = 1, ..., m) \\ \sum_{j=1}^{n} Y_{ij}\lambda_j - s_r^+ = Y_{rj0} \quad (r = 1, ..., l) \\ \lambda_j, \theta, s_i^-, s_r^+ \geqslant 0 \end{cases} \tag{1}$$

where $\theta$is the efficiency score of the DMU_{j0};ε is a non-Archimedean infinitely small quantity that can be taken as 10^{-6} [40], λ_j represents the proportion to which $DMU_j$is used to construct the composite unit for DMU_{j0}; s_i^- and s_r^+ are slack variables.

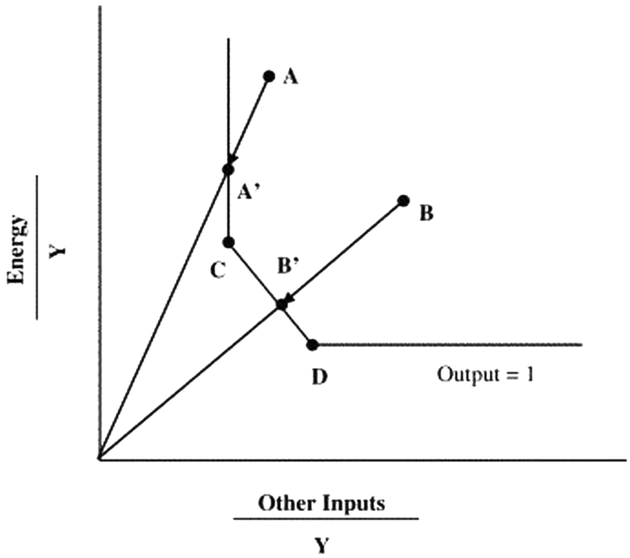

Fig. 2. Best practice, target and adjustment in an input-oriented DEA.

DEA can construct a non-parametric piecewise frontier composed of DMUs that have the optimal efficiency over the datasets, and the frontier is used for comparative efficiency measurement. Therefore, when calculating the TFEE of the EU-15 and 60 BRI countries in the same model, they are comparative due to the common constructed frontier. Those DMUs which are located on the efficiency frontier deliver their maximum outputs generated by taking the minimum level of inputs, are efficient DMUs, and own the best efficiency among all DMUs. The most efficient point on the frontier can be identified as a target for the inefficient DMUs by solving the linear programming problem in Eq. (1) to obtain the optimal value θ^* [41]. When $\theta^* = 1$ and $s^- = s^+ = 0$, the DMU minimizes the quantities of inputs required to meet output levels. When $\theta^* = 1$ and $s^- \neq 0$ or $s^+ \neq 0$; or $\theta^* < 1$, the DMU is not efficient and has the space to minimize its inputs to meet the output level.

The target energy input is the practical minimum level of energy input in a region in order to perform at the optimal efficiency of energy consumption. Fig. 2 illustrates how a point with a practical minimum input on the frontier can be identified in DEA. The maximum level Y output by the DMUs located on the frontier is normalized to unity and generated from the energy input and other inputs which are also normalized by dividing Y. Point B is the actual input set and point B′ is the projected point on the frontier for DMU B as the target in order to improve its efficiency accordingly by reducing the radial adjustment BB′, meaning the total amount for inputs adjusted by a DMU so as to reach its optimal production efficiency [42].

Hu and Wang [42] define TFEE as the ratio of target energy input to actual energy input with other inputs unchanged. Compared with such other single energy efficiency indicators as energy intensity, TFEE assesses the energy consumption to produce GDP based on multi input factors, with TFEE calculated by

$$TFEE_j = \frac{E_j^{tar}}{E_j^{act}} = \frac{\theta^* E_j^{act} - s^-}{E_j^{act}} \tag{2}$$

where $TFEE_j$ denotes the TFEE and E_j^{tar} and E_j^{act} represent the target and actual energy input respectively of country j. The target energy input represents the practical minimum level of energy input taken as a target in a region in order to perform at the optimal efficiency of energy consumption. The level of target energy input is identified through Eq. (1) in conjunction with other inputs to produce an economic output. Because the target energy input is always smaller than or equal to actual energy input, TFEE always ranges from 0 to 1. A larger TFEE means the actual energy input is closer to the suggested target energy input, which represents high efficiency. Conversely, when TFEE approaches 0, the actual energy input is far more than the suggested target energy input, which represents low efficiency in terms of energy utilization.

4.2. Convergence analysis of TFEE by the panel quantile approach

After calculating the TFEE of the BRI countries and EU-15, the study explores β-convergence in the BRI countries' TFEE, because β-convergence discloses the rate by which economies close the gap annually between current levels of TFEE and balanced growth levels compared with σ-convergence. TFEE β-convergence refers to regions with relatively lower initial TFEE levels having a larger growth rate than regions with higher initial TFEE levels, with negatively correlated growth rates and initial TFEE levels [43]. β-convergence includes absolute β-convergence and conditional β-convergence – the former indicating that all countries share the same steady path and the latter that countries converge to their own steady state level instead of a common level [15]. Conditional β-convergence consists of control variables that are not considered in absolute β-convergence. The basic model of absolute TFEE β-convergence is

$$\ln TFEE_{j,t} - \ln TFEE_{j,t-1} = \chi + \beta_a \ln TFEE_{j,t-1} + \upsilon_{jt} \tag{3}$$

where $TFEE_{j,t}$ is the TFEE in country j in year t; $\ln TFEE_{j,t} - \ln TFEE_{j,t-1}$ represents the TFEE growth rate in country j from year $t-1$ to t; β_a represents the absolute convergence coefficient; χ represents the constant term; and υ_{it} is the error term.

Different countries may converge to their own steady path by considering their differences in economic development and energy utilization; hence, the control variables are added to analyze the conditional β-convergence based on Eq. (3). While economic development, economic structure, technology level, and energy price are the key factors affecting changes of energy efficiency in general [44,45], control variables are needed for energy efficiency. Here, we use the control variables: (1) economic development indicators (GDP per capita and urbanization); (2) economic structure indicators (industry structure and energy structure); (3) technology level indictors (technology diffusion from trade and FDI, and indigenous innovation from R&D investment).

The model of conditional TFEE β-convergence is then

$$\ln TFEE_{j,t} - \ln TFEE_{j,t-1} = \chi + \beta_c \ln TFEE_{j,t-1} + \alpha X_{j,t} + \upsilon_{j,t} \tag{4}$$

where $X_{j,t}$ is the vector of control variables. $X_{j,t} = [\ln PGDP_{j,t}, \ \ln URBAN_{j,t}, \ \ln INS, \ \ln ENS, \ \ln TRADE, \ \ln FDI, \ \ln RD]'$, including GDP per capita, urbanization rate, ratio of secondary industry, ratio of no-coal consumption, ratio of total trade to GDP, FDI and ratio of RD to GDP in country j and year t, respectively. The other variables have the same meaning as in Eq. (3). β_c denotes the TFEE conditional convergence coefficient. If β_c is significantly negative, the conditional TFEE β-convergence hypothesis in BRI countries is supported. Low TFEE BRI countries appear to be growing faster. According to Islam [46], the relationship between convergence rate (ω) and the convergence coefficient (β_c) can be expressed as

$$\omega = -\ln(\beta_c + 1) \tag{5}$$

where ω measures the rate at which the TFEE in a country along the BRI moves from its initial efficiency to a balanced efficiency growth or its own steady state level, also the catch-up rate at which a backward country closes on the frontier countries [47]. A higher absolute value of the convergence coefficient signifies a faster rate. The conditional TFEE β-convergence of BRI countries relative to the frontier of TFEE of convergence is further analyzed as [48]

$$g_{j,t} - g_{f,t} = \chi + \beta_{cf}(\ln TFEE_{j,t-1} - \ln TFEE_{f,t-1}) + \alpha X_{j,t} + \upsilon_{j,t} \tag{6}$$

where $g_{j,t} = \ln TFEE_{j,t} - \ln TFEE_{j,t-1}$, and $g_{f,t}$ are the TFEE growth rates of frontier EU countries; and β_{cf} is the TFEE convergence coefficient of BRI countries relative to frontier countries, measuring whether TFEE grows faster in BRI countries that initially fall behind the frontier.

Table 1
Summary of descriptive statistics [a.]

Variable	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque-Bera
g	−0.001	0.001	0.808	−0.825	0.099	−2.620	31.450	26500.250***
ln *TFEE*	−0.770	−0.743	0.000	−2.176	0.484	−0.284	2.820	11.218***
ln *PGDP*	8.666	8.709	11.162	5.597	1.154	−0.233	2.290	22.876***
ln *URBAN*	−0.569	−0.487	0.000	−1.823	0.342	−0.959	4.003	148.358***
ln *INS*	3.459	3.470	4.273	2.067	0.320	−0.359	4.616	98.938***
ln *ENS*	−0.304	−0.179	0.000	−1.554	0.358	−1.285	3.791	229.142***
ln *TRADE*	4.442	4.484	6.090	−0.671	0.625	−2.876	23.912	14896.240***
ln *FDI*	7.186	7.388	11.717	0.000	2.185	−0.989	5.021	253.287***
ln *RD*	3.806	3.934	6.088	0.465	0.992	−0.470	3.538	37.172***

[a] ***denotes significance at the 1% level.

Ordinary least squares estimation focusing solely on mean effects can lead to inaccurate estimates of coefficients or the omission of important relationships [49], whereas quantile regression can provide a more detailed and complete relationship between the TFEE growth rate and initial TFEE throughout the conditional distribution [50]. Quantile regression is an extension of standard regression, providing a complete description of a conditional distribution. Hence, a panel quantile approach is established with fixed effects that controls for individual heterogeneity, to obtain the conditional β-convergence coefficients of the entire conditional TFEE growth rate distribution of

$$Q_{g_{j,t}}(\tau_k|\mu_j, x_{jt}) = \beta_{c\tau}\ln TFEE_{j,t-1} + \alpha_\tau X_{j,t} + \mu_j \tag{7}$$

where μ_j denotes the unobservable individual effect; and$\tau$is the TFEE growth rate quantile and ranges from 0 to 1. Koenker [51] proposes a general method to estimate the fixed effects quantile regression for panel data. Applying his principle to Eq. (7) provides the estimation

$$\arg\min\sum_{k=1}^{K}\sum_{t=1}^{T}\sum_{j=1}^{N} w_k\rho_{\tau_k}(g_{j,t}-\mu_j-\beta_{c\tau}\ln TFEE_{j,t-1}-\alpha_\tau X_{j,t}) + \lambda\sum_{j=1}^{N}|\mu_j| \tag{8}$$

where $\rho_\tau(u) = u(\tau - I(u<0))$is the check function, and $I(u<0) = \begin{cases}1, & u<0\\ 0, & u\geqslant 0\end{cases}$ is the indicator function; andw_k is the weight that controls the relative influence of the kth quantile on the estimation of the μ_j. Following Alexander et al. [52] and Lamarche [53], we take the equal weight, i.e., $w_k = \frac{1}{K}$; λ is a tuning parameter that reduces the individual effects to zero to improve the estimation performance [51]. If $\lambda = 0$, then the penalty term disappears and the usual fixed effects estimator is obtained. However, if λ becomes very large, the estimation of the model without individual effects is obtained. Here, we set $\lambda = 0.5$ [54,55]. Thus, the coefficients $\beta_{c\tau}$ and $\alpha_\tau$are estimated at the τ quantile of the conditional distribution.

Moreover, we study whether the economic, structure, and technology factors (income, urbanization rate, industry structure, energy structure, trade, FDI, and R&D) accelerate or decelerate the convergence process of TFEE. An interaction between the initial value of TFEE and the factor (income or urbanization rate, industry structure, energy structure, trade, FDI, R&D) is used as

$$\ln TFEE_{j,t} - \ln TFEE_{j,t-1} = \beta_c\ln TFEE_{j,t-1} + \gamma\ln Z_{j,t} + \delta\ln TFEE_{j,t-1} * \ln Z_{j,t} + \alpha X_{j,t} + \mu_j + \upsilon_{j,t} \tag{9}$$

where $Z_{j,t}$ is $\ln PGDP_{j,t}$ (or $\ln URBAN_{j,t}$, $\ln INS$, $\ln ENS$, $\ln TRADE$, $\ln FDI$, $\ln RD$). The TFEE convergence process is slower for the least advanced countries if $\delta > 0$ and faster if $\delta < 0$, expecting β_c to remain negative and statistically significant. In this way, the factors affecting the TFEE convergence rate can be identified. Using panel quantile regression, the complete description of a conditional distribution in terms of the interactions is exhibited, to identify the impact of the factors involved on BRI TFEE convergence as

$$\arg\min\sum_{k=1}^{K}\sum_{t=1}^{T}\sum_{j=1}^{N} w_k\rho_{\tau_k}(g_{j,t}-\mu_j-\beta_{c\tau}\ln TFEE_{j,t-1}-\delta_\tau\ln Z_{j,t} - \delta_\tau\ln TFEE_{j,t-1} * \ln Z_{j,t} - \alpha_\tau X_{j,t}) + \lambda\sum_{j=1}^{N}|\mu_j| \tag{10}$$

4.3. Data definition

It is should be noted that there are around 65 countries along the BRI, whereas the sample in this paper comprises 60 BRI countries of which 10 are EU countries, the other 5 countries, i.e., Afghan, Palestine, Laos, Maldives, and Montenegro are excluded because of data unavailability. 15 non-BRI EU countries (EU-15) are also added as the benchmark for comparison. A list of the 75 countries can be found in Table 2.

The panel data includes the 1995–2015 GDP, capital stocks, labor and primary energy consumption of all 75 countries, and their 1996–2015 GDP per capita, urbanization rate, ratio of secondary industry added values to GDP, ratio of non-coal consumption to total energy consumption, ratio of total trade to GDP, FDI, and the ratio of R &D expenditure to GDP of the 60 BRI countries. The GDP, labor, GDP per capita, urbanization rate, ratio of secondary industry added value to GDP, ratio of total trade to GDP, and ratio of R&D expenditure to GDP are from the World Development Indicators (WDI) database of the World Bank; primary energy consumption and no-coal consumption are from the International Energy Agency (IEA); FDI are from the United National Conference on Trade and Development (UNCTAD); the 1995–2014 capital stocks are from the Penn World Table, version 9.0 [56]; and the 2015 capital stocks are calculated from [57]

$$K_{j,2015} = I_{j,2015} + (1-\psi_j)K_{j,2014} \tag{11}$$

where $I_{j,2015}$ is gross fixed capital formation of country $j$in 2015; $\psi_j$is the depreciation rate, set here as 6% [58]; $K_{j,2014}$ is the capital stock of country j in 2014. The 2015 gross fixed capital formation is from the WDI. GDP, GDP per capita, capital stocks, and FDI are all measured at 2010 constant USD price. It is worth noting that the R&D expenditure ratio data are absent in several countries, so we use the unbalanced panel data. Table 1 reports the descriptive statistics of the variables. As seen in Table 1, the distribution of TFEE growth (g) is negative skewness and has an obvious peak and fat tails, because the Skewness statistic is less than 0, and the Kurtosis statistic is far more than 3. Besides, the Jarque–Bera tests significantly reject the null hypotheses of normality, demonstrating the non-normal distribution of all the variables. Thus, the distribution of the dataset demonstrates the panel quantile regression is more appropriate to estimate the TFEE convergence coefficients.

Table 2
1995–2015 average TFEE of the BRI countries and EU-15 countries.

BRI Countries	Average TFEE	Rank	BRI Countries	Average TFEE	Rank	BRI Countries	Average TFEE	Rank	EU-15 Countries	Average TFEE	Rank
Albania	0.4742	45	Bahrain	0.4410	49	Tajikistan	0.1755	73	Austria	0.7805	13
Belarus	0.3591	61	Cyprus	0.9736	5	Turkmenistan	0.1579	75	Belgium	0.6395	26
Bosnia and Herzegovina	0.5024	38	Egypt, Arab Rep.	0.5892	31	Uzbekistan	0.1980	71	Denmark	0.9982	3
Bulgaria	0.5401	37	Georgia	0.4219	52	Brunei Darussalam	0.8388	11	Finland	0.5430	36
Croatia	0.6056	30	Greece	0.9764	4	Cambodia	0.4289	50	France	0.7345	20
Czech Republic	0.4859	42	Iran, Islamic Rep.	0.3356	65	Indonesia	0.3373	63	Germany	0.7656	15
Estonia	0.4460	47	Iraq	0.5812	33	Malaysia	0.4655	46	Ireland	0.9067	9
Hungary	0.4850	43	Israel	1.0000	1	Myanmar	0.7572	19	Italy	0.7751	14
Latvia	0.4791	44	Jordan	0.3878	57	Philippines	0.4067	53	Luxembourg	0.9993	2
Lithuania	0.4947	41	Kuwait	0.9106	8	Singapore	0.9359	7	Malta	0.7613	16
Macedonia, FYR	0.4271	51	Lebanon	0.4966	40	Thailand	0.3195	66	Netherlands	0.7608	17
Moldova	0.3036	67	Oman	0.6154	29	Vietnam	0.3810	60	Portugal	0.5831	32
Poland	0.6908	23	Qatar	0.9423	6	Bangladesh	0.3844	59	Spain	0.6396	25
Romania	0.4021	56	Saudi Arabia	0.6237	28	India	0.2927	68	Sweden	0.7219	21
Serbia	0.2614	70	Syrian Arab Republic	0.4447	48	Nepal	0.2858	69	United Kingdom	0.7601	18
Slovak Republic	0.5579	35	Turkey	0.8069	12	Pakistan	0.3363	64			
Slovenia	0.6445	24	United Arab Emirates	0.8482	10	Sri Lanka	0.5016	39			
Ukraine	0.1736	74	Yemen, Rep.	0.5698	34	Mongolia	0.1949	72			
Armenia	0.6383	27	Kazakhstan	0.4031	55	Russian Federation	0.4043	54			
Azerbaijan	0.7120	22	Kyrgyz Republic	0.3588	62	China	0.3849	58			

5. Empirical results

5.1. Total-factor energy efficiency

The 1995–2015 annual average TFEE of the 75 countries obtained from Eqs. (1) and (2) are summarized in Table 2 and Fig. 3. As can be seen, the results for EU-15 are higher than the 60 BRI countries. This is to be expected, as the EU-15 countries have highly developed economies with advanced industrialization and technology.

For the BRI countries, the Middle East and West Asia are the highest, followed by Southeast Asia, Central and Eastern Europe, China, South Asia, Russia and Mongolia, and Central Asia. As seen in Table 2, the high TFEE countries include Israel, Greece, Qatar, Cyprus, United Arab Emirates, and Kuwait. Such countries as Qatar, United Arab Emirates, and Kuwait, have abundant oil resources that earn a considerable amount of money from oil export, oil transport, and oil processing, and their income per capita is far more than the high-income country baseline. Moreover, the quality of oil is much better in these areas. The TFEE in Singapore and Brunei Darussalam in Southeast Asia are also relatively high, which is closely related to their high economic development and high-income levels. Brunei Darussalam is one of the wealthiest countries relying on energy exports [59], while Singapore's economy is driven by exporting manufacturing products in the context of high trade openness, technology levels, and a high education level [60].

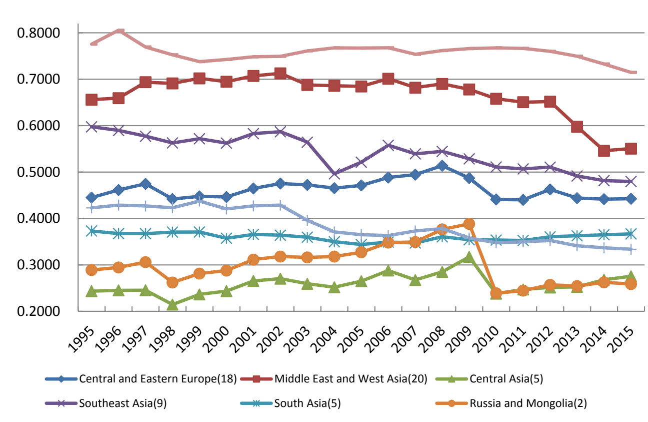

Fig. 3. Annual average TFEE of the seven BRI regions and EU-15.

In contrast, from Table 2, such Central Asian countries as Turkmenistan, Uzbekistan, and Tajikistan with a relatively low economic development level, have a relatively low average TFEE, which indicates that the energy input in these countries is far more than the targeted energy input in production activity. As elaborated by Zhang et al. [61], these countries have lower levels of economic development and a weaker infrastructure. As a result, with the rapid development of their economy and progress of energy technology, they have a great potential for energy conservation. It can be found in Table 2 that the energy utilization efficiency in China is ranked 58rd of the 75 EU and BRI countries – much lower than the EU-15, Middle East and West Asia, Southeast Asia, Central and Eastern Europe.

In terms of time, the BRI regions experienced an increasing trend before 2009, decreasing from 2009 to 2010, and slowly increasing thereafter. The decrease would have been mainly influenced by the global finance crisis, with the weakening economies worldwide leading to excess inputs when producing a certain level of output - the increase after 2010 in most regions being influenced by recovering economies.

5.2. The catch-up effect within BRI countries and between BRI-EU

To examine whether backward BRI countries with initial low TFEE are catching up with the frontier BRI countries, and whether the backward BRI countries are catching up the benchmark EU countries (on the condition of different TFEE growth rates, as well as their heterogeneous characteristics of convergence rates), we estimate the corresponding heterogeneous convergence coefficients at 95 quantiles by panel quantile regression. Fig. 4a(1) and a(2) shows the convergence coefficients of the 60 BRI countries and relative to EU-15 at 95 quantiles ranging from 0.05 to 0.95. Fig. 5 shows the panel quantile regression results of the control variables ranging from 0.05 to 0.95. The tails need to be treated with caution as they can be driven by a small number of extreme values [62]; therefore, the coefficients from the 0.05 to 0.95 quantiles are analyzed. The shaded areas indicate the corresponding 90% confidence intervals. If the confidence intervals encompass the horizontal zero axis, the corresponding estimates are not significantly different from zero.

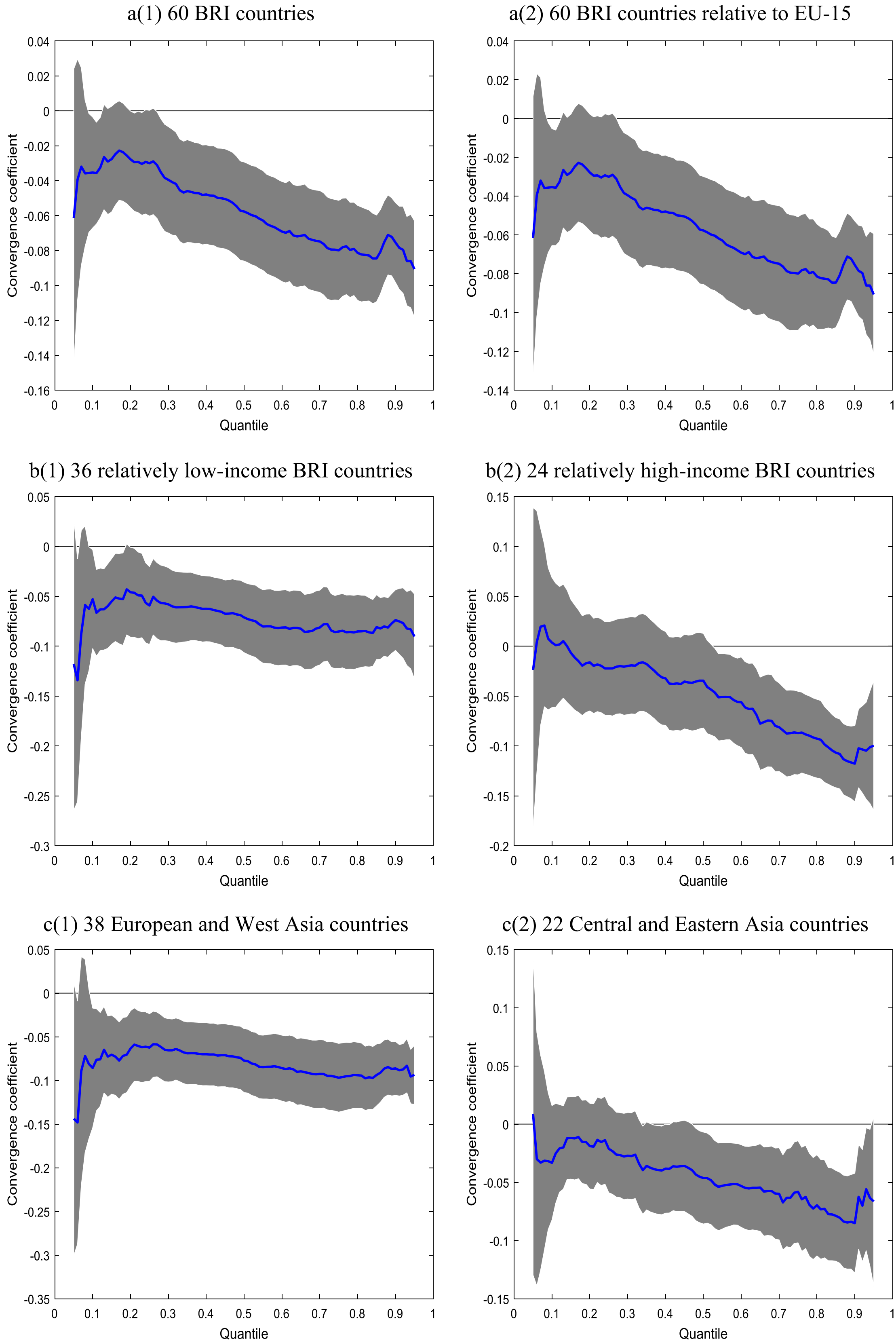

Fig. 4. Change in convergence coefficients of BRI countries by quantile.

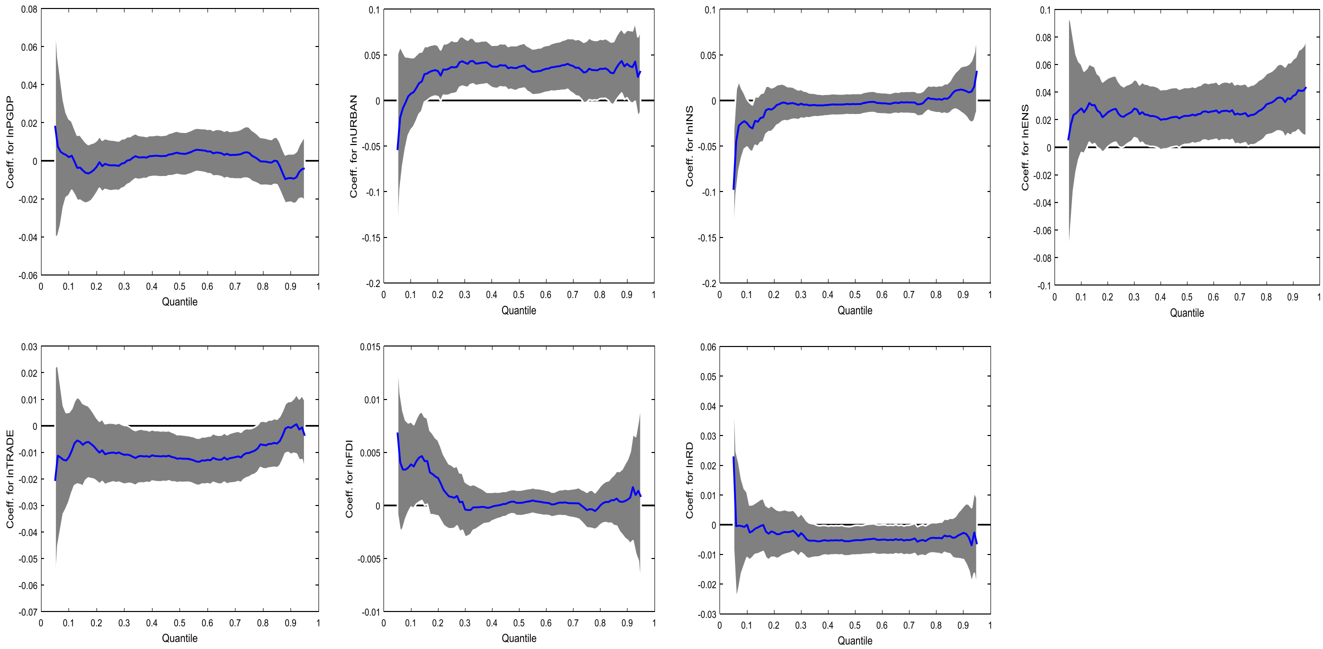

Fig. 5. Coefficients of the control variables by quantiles in TFEE convergence regression of 60 BRI countries.

The first observation from Fig. 4 is that backward countries with initial low TFEE almost catch up (converge), especially when the TFEE growth rate is greater. The convergence coefficients in Fig. 4a(1) and a (2) are significantly negative at the 10% significance level after the 0.25 quantile. This indicates that BRI countries with a low initial TFEE are catching up with countries with high TFEE levels, and more significantly when the TFEE growth rate is greater. This is also applicable to the catch-up process of BRI countries relative to EU-15. In contrast with Han et al. [63], who find that energy efficiency in 37 BRI countries has a significant conditional convergence, our results indicate that convergence is more significant when the efficiency growth rate is greater.

5.3. The catch-up effect within BRI groups divided by income and location

Given the heterogeneity of TFEE convergence rate within BRI countries with different characteristics, we further divide the 60 BRI countries into two groups. The first group comprises the 24 relatively high-income countries whose average income per capita is more than USD 10,000 and the other 36 relatively low-income countries. The second group is the 38 countries located in Central and Eastern Europe and West Asia, and remaining 22 countries located in Central and Eastern Asia.

Fig. 4b and c shows the convergence coefficients of the income group and location group at the 95 quantiles ranging from 0.05 to 0.95, respectively. [5]This shows that the convergence coefficients in Fig. 4b(2) and c(2) are significantly negative at the 10% significance level after the 0.52 quantile and 0.48 quantile, respectively; and the convergence coefficients in Fig. 4b(1) and c(1) are significantly negative at the 10% significance level for almost all quantiles. This finding also supports the first above-mentioned observation, i.e., the BRI countries with a low initial TFEE catch up with countries with a high TFEE level.

Second, the TFEE convergence rate of BRI countries has an increasing trend with increased TFEE growth rate. All the significant convergence coefficients in Fig. 4 are negative, with the absolute values indicating an increasing trend of convergence rate because of the declinate lines. This suggests that, with the increase of TFEE growth rate, the convergence coefficient and rate are greater. Countries with a higher TFEE growth rate converge to their own steady state (or to the TFEE frontier, i.e., EU-15), at a higher convergence rate. The backward BRI countries with a low initial TFEE catch up with the frontier countries at a faster rate if they increase their TFEE growth rate.

Third, the TFEE in high-income BRI countries converges at a faster rate when the TFEE growth rate is greater. At low quantiles, the convergence coefficients in low-income BRI countries are greater than the high-income ones while, at high quantiles, they are significantly smaller. This may be because, in low-income BRI countries, the level of high TFEE is not as influential as in the high-income ones. The catch-up process in the high-income BRI countries appears to be more difficult at a high TFEE level when the TFEE growth rate is small. Therefore, a small TFEE growth rate exhibits significant and insignificant convergence in low-income and high-income BRI countries respectively while, when the TFEE growth rate is greater, the advanced technologies and management of high-income countries produces a higher TFEE convergence rate in countries with high or frontier TFEE compared to low-income countries.

Finally, the TFEE convergence rate in Eastern Europe and West Asia countries is faster than Central and Eastern Asia countries. As is seen, when TFEE growth is small, the TFEE in Central and Eastern Asia countries is divergent, while that in Eastern Europe and West Asia countries is convergent. When TFEE growth is greater, the TFEE is convergent in both regions. Furthermore, the convergence coefficients in Eastern Europe and West Asia countries range from almost 0.06 to 0.09, greater than that in Central and Eastern Asia countries, which range from 0.04 to 0.08.

As for the control variables in Fig. 5, the urbanization rate and no-coal consumption ratio has a small positive impact on TFEE growth; and trade and R&D have a constrained impact on the TFEE growth of BRI countries in general, whereas GDP per capita, industry structure, and FDI have no significant impact on TFEE growth. TFEE growth is a result of the improvement in energy utilization and the environment compared to the past. Most urbanization rate coefficients are significantly positive. This is mainly because the industrial upgrading and change in lifestyle and consumption patterns as the urbanization rate increases are beneficial to TFEE growth [64]. The positive impact of the

[5] The convergence coefficients of the income group and location group relative to EU-15 at 95 quantiles are very similar to their own convergence coefficients, so we do not exhibit them in the Figures.

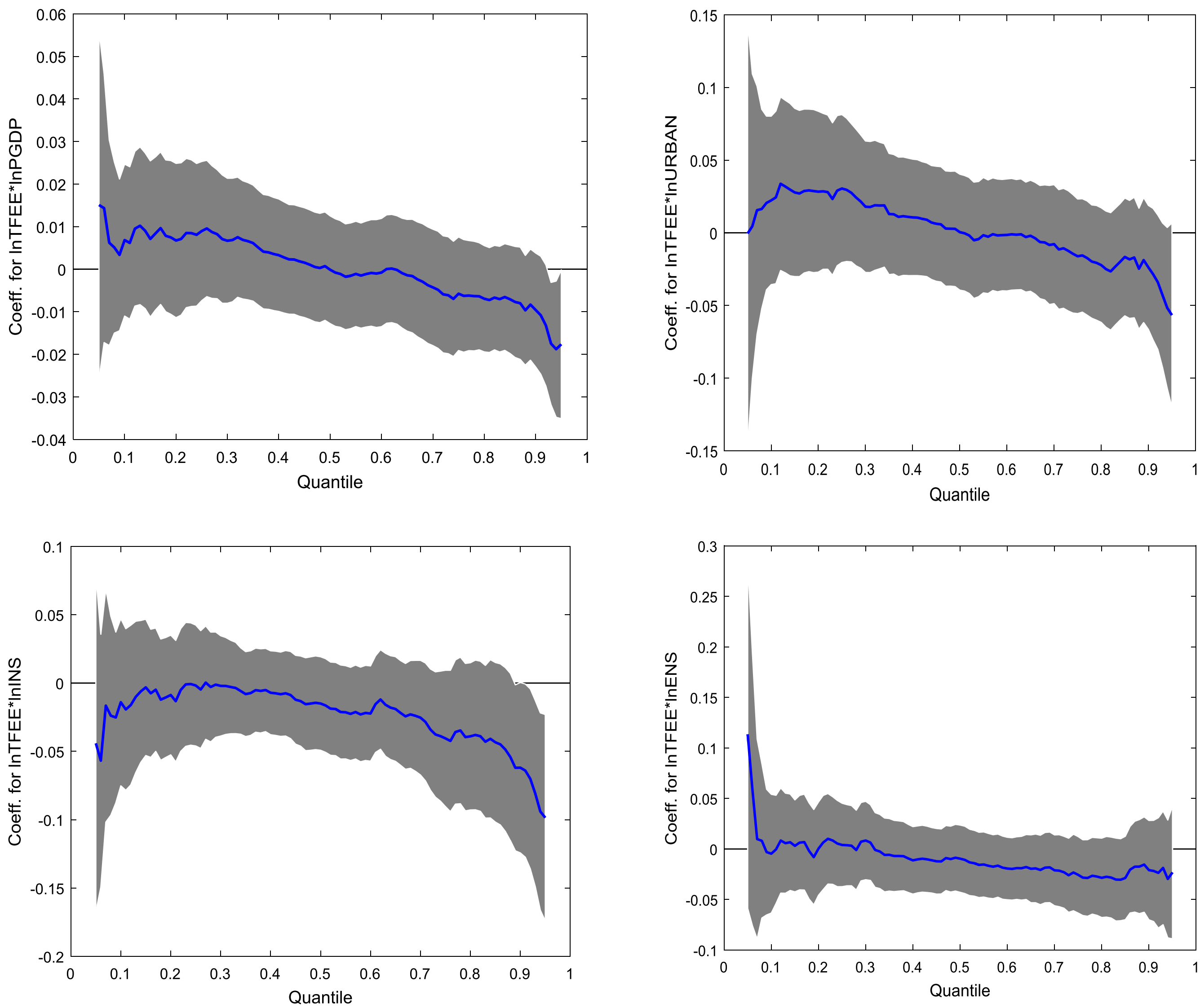

Fig. 6. The influence of economic factors and structure factors on TFEE convergence.

no-coal consumption ratio on TFEE growth is due to the greater efficiency of liquid or gas fuel. The trade coefficients are negative for most quantiles. This suggests that trade has little negative impact on TFEE growth in general. Trade structures are greatly different in BRI countries [65]. In particular, most BRI countries are developing countries, and trade is one of the most important drivers of economic development. Middle Eastern oil-rich countries mainly export oil and oil products, while industrialized Asian countries mainly export manufactured products; trade may stimulate international specialization and spatial separation, resulting in developed countries with a comparative advantage in clean production being cleaner, while developing countries with a comparative advantage of energy-intensive industry are more pollutant, and trade thus has little negative impact on the TFEE growth of BRI countries overall. The negative impact of R&D on TFEE growth may mainly result from lower R&D innovation and absorption capacity. However, the coefficients of GDP per capita, industry structure, and FDI are insignificant at most quantiles, which indicates that economic development, industry adjustment, and FDI have no significant influence on the TFEE growth of BRI countries overall.

5.4. The R&D innovation and absorption effect on TFEE convergence

We study the factors that may speed up or slow down the BRI countries' TFEE catch-up rate by adding interactions between economic factors (income and urbanization), structure factors (industry structure and energy structure), technology factors (trade, FDI, and R&D), and the initial TFEE value (see Eqs. (9) and (10)). Fig. 6 shows the impact of the economic factors and structure factors on TFEE convergence. The coefficients of ln *TFEE* are also negative at some quantiles. The impacts of these factors are not statistically significant at the 10% significance level. It is hard to identify whether income, urbanization industry structure, and energy structure have the small positive or negative impact on TFEE convergence, although the coefficients are located in the negative domain, especially at larger quantiles.

Next, we focus on the impact of technology factors on TFEE convergence. Fig. 7 shows the impacts of trade and FDI on TFEE convergence. Fig. 8 shows the impacts of R&D on TFEE convergence. The ln *TFEE* coefficients are significantly negative at most quantiles for R&D and FDI, and at the quantiles of 0.4–0.67 for trade. Focusing on their impact on TFEE convergence, we find that R&D slows the TFEE convergence rate at the 10% significance level on a whole, while FDI and trade have no significant influence on TFEE convergence.

Because R&D investment not only generates or stimulates innovation, but also enhances the ability of enterprises to learn about existing knowledge and information and promotes the spillover of knowledge and technology, R&D investment has two ways of improving innovation

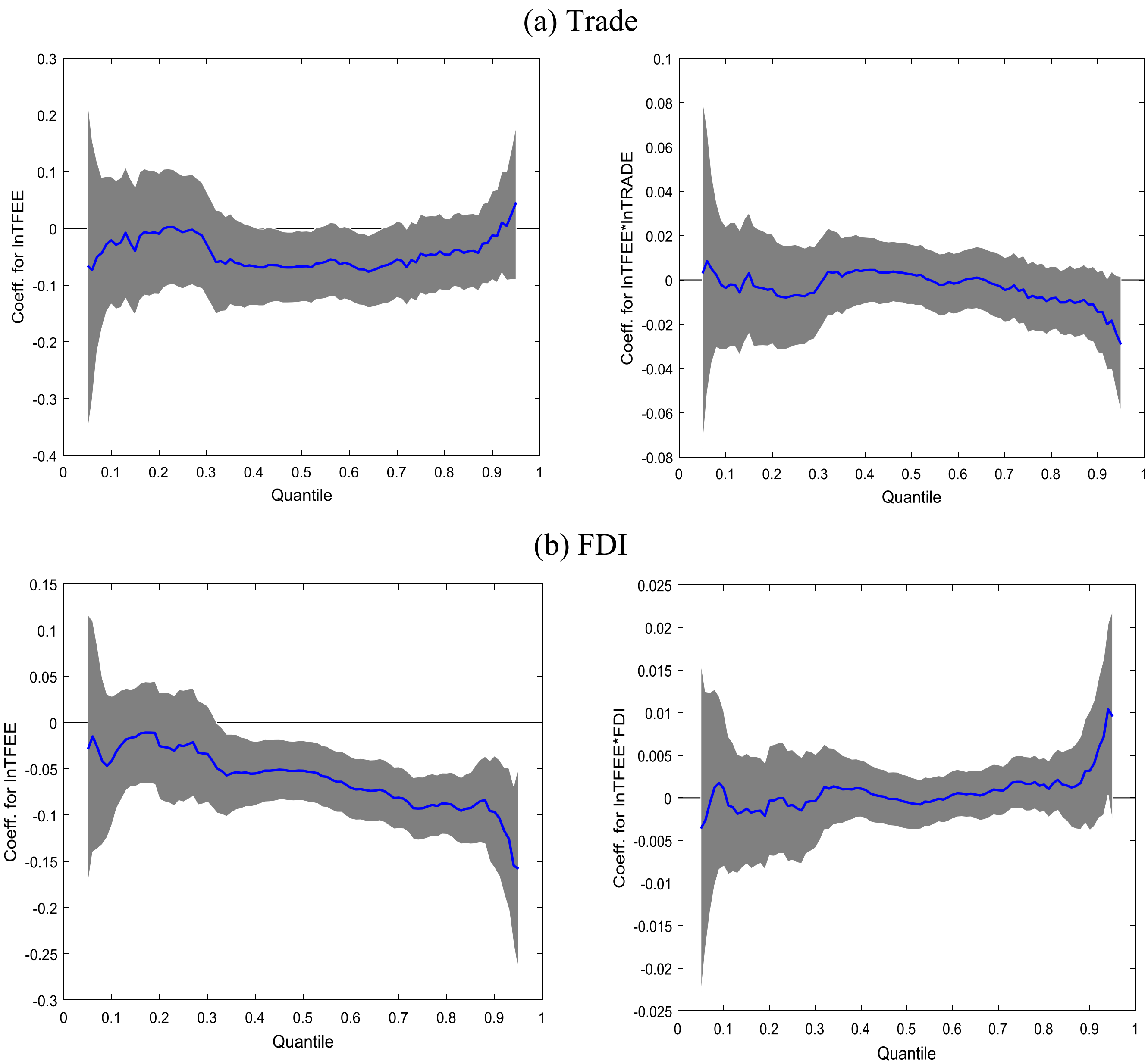

Fig. 7. The impact of trade and FDI on TFEE convergence.

capability and the absorption capability of spillover technology [66]. The R&D absorption capability for spillover technology can be measured by the interaction between R&D investment and FDI or trade [67]. Therefore, we further examine if R&D investment slows down the TFEE convergence of BRI countries because of their weak R&D absorption capability. Take FDI for example, adding interactions $\ln TFEE{*}\ln RD$ (R&D innovation capability), $\ln TFEE{*}\ln FDI$ (FDI technology diffusion), and $\ln TFEE{*}\ln FDI{*}\ln RD$ (R&D absorption capability for FDI technology diffusion) based on Eqs. (9) and (10). The coefficient of $\ln TFEE{*}\ln FDI{*}\ln RD$ denotes the impact of R&D capability on absorbing FDI technology diffusion on TFEE convergence. A significantly negative coefficient indicates that the advanced technologies embodied in FDI are well absorbed, resulting from a strong R&D absorption capability, and the FDI technology diffusion is effective at narrowing the technology gap and promoting TFEE convergence. The results are also shown in Fig. 8. The effects of R&D innovation capability, FDI, and trade technology diffusion are not significant and are not shown here. The insignificant coefficients of the interaction $\ln TFEE{*}\ln FDI{*}\ln RD$ suggest that the advanced technologies embodied in FDI are not well absorbed because of a weak R&D absorption capability, and the FDI or trade technology diffusion are insufficiently effective in promoting TFEE convergence. However, the coefficients of the interaction $\ln TFEE{*}\ln TRADE{*}\ln RD$ are significantly negative at quantiles 0.75–0.93, which indicates that, when TFEE growth is greater, the R&D absorption capability of technology diffusion from trade is helpful in narrowing the technology gap and accelerating TFEE convergence.

5.5. Robustness analysis

Robustness checks are conducted in this section to test the validity of the results by considering different values of 1 and 0.25 for λ. As the changes in the BRI countries' TFEE convergence coefficients are similar to EU-15, only the BRI countries' convergence is checked. These are reported in Fig. 9. The convergence coefficients in Fig. 9a(1) and a(2) are significantly negative at the 10% level after the 0.3 quantile; the convergence coefficients in Fig. 9c(1) and c(2) are significantly negative at the 10% level after the 0.52 and 0.48 quantile, respectively; the

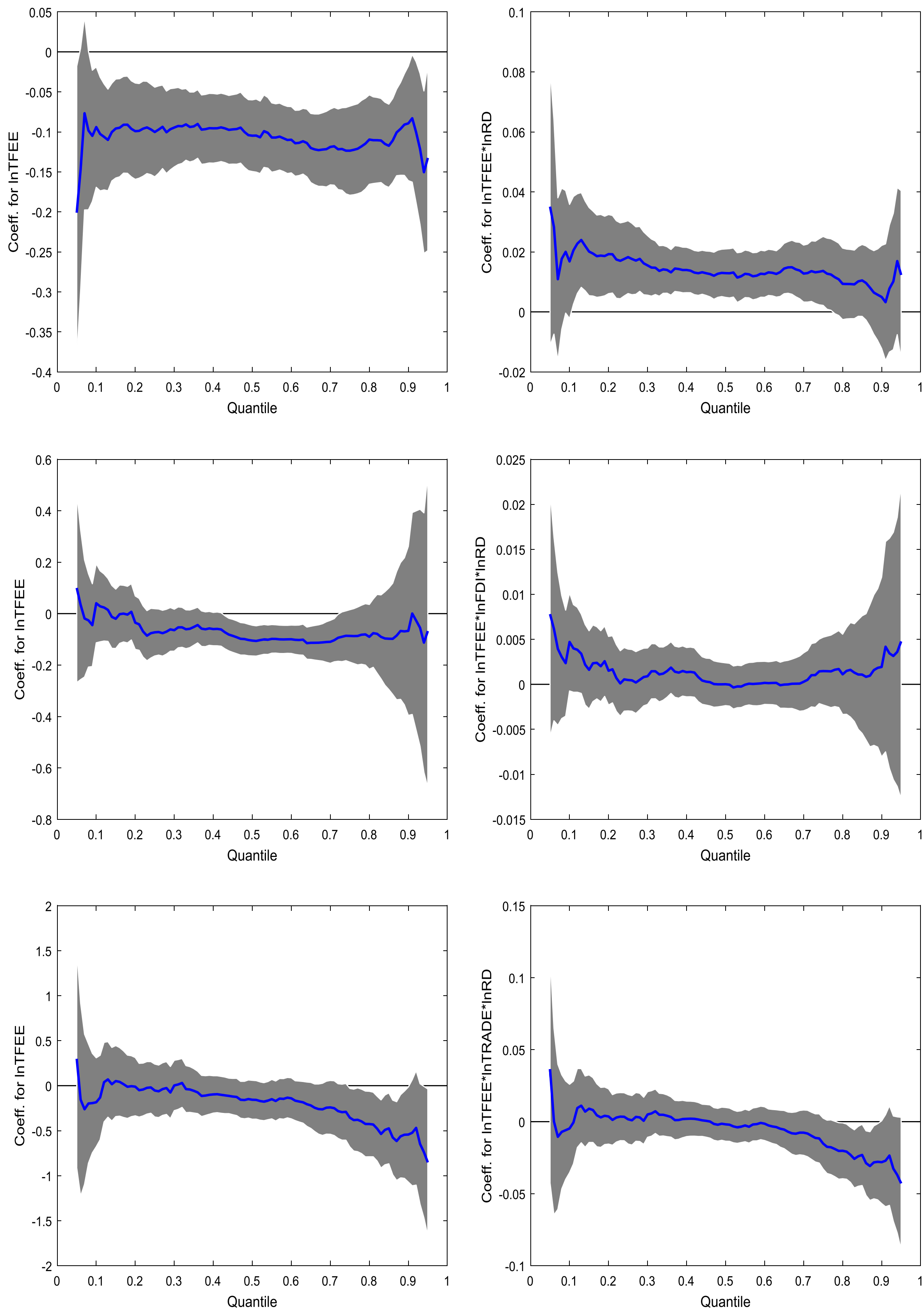

Fig. 8. The impact of R&D capability on absorbing FDI or trade technology diffusion on TFEE convergence.

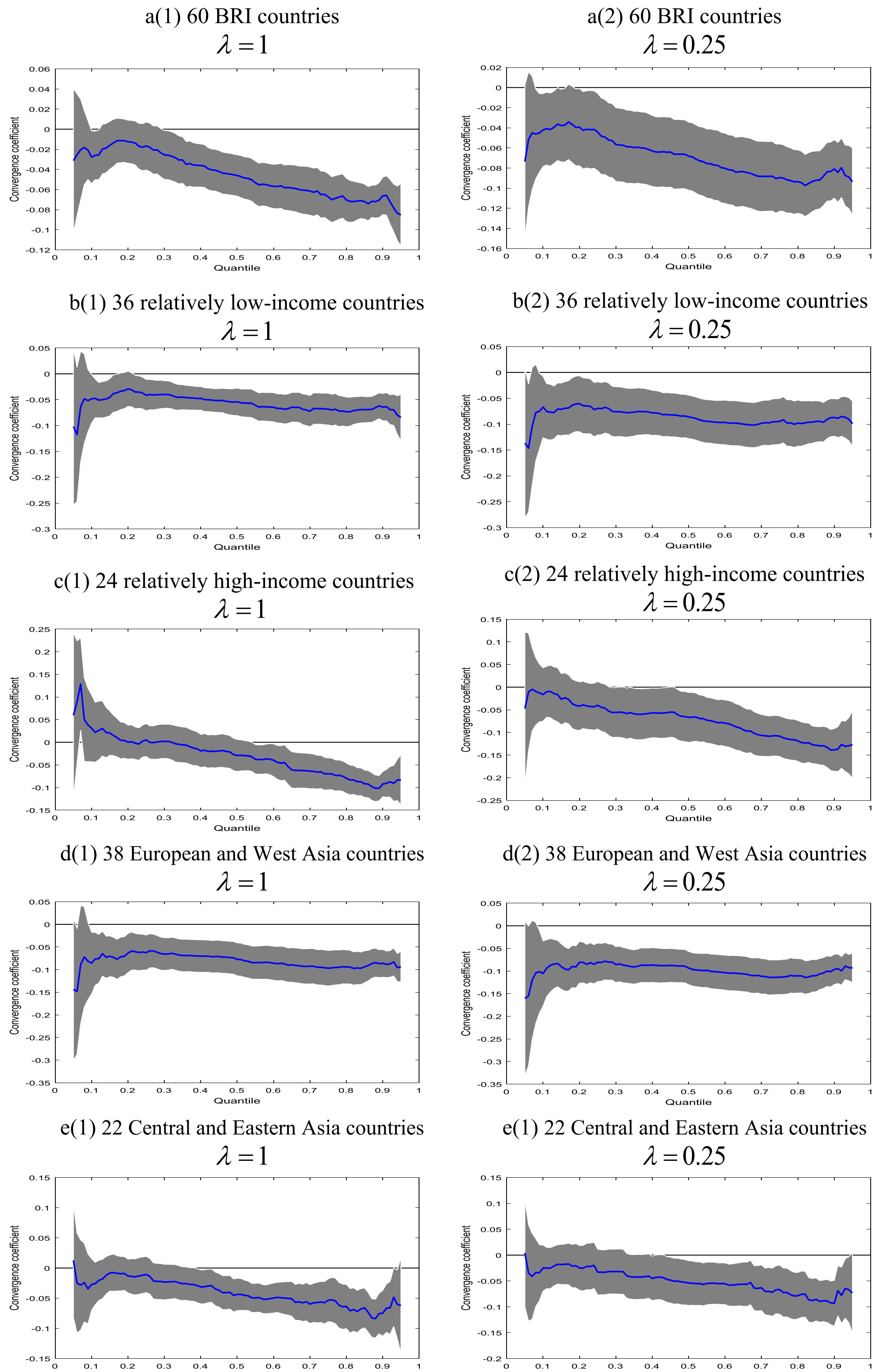

Fig. 9. Robustness analysis with alternative values of λ: convergence coefficients of BRI countries.

convergence coefficients in Fig. 9b and d are significantly negative at the 10% level at almost all quantiles; and the convergence coefficients in Fig. 9e(1) and e(2) are significantly negative at the 10% level after the 0.4 and 0.43 quantile, respectively. These are very similar to the results in Fig. 4, where $\lambda = 0.5$. The notion that the 60 countries' TFEE does not significantly converge when their TFEE growth is smaller is therefore supported. The sizes and trend of the convergence coefficients are very similar to the results in Fig. 4, which also indicates the robustness of the findings.

6. Discussion

It is confirmed that the BRI countries' TFEE are generally converging to their own steady state or to the frontier EU-15 countries, and the convergence rate is increasing with the increase in TFEE growth rate. Countries with a greater TFEE growth rate have three possible characteristics from the perspectives of scale effect, structure effect, and technology effect.

(1) That they accelerate urbanization. For example, according to the TFEE results, the countries with a higher TFEE growth rate include the Czech Republic, whose TFEE rose from 0.43 in 2000 to 0.56 in 2008, Latvia from 0.31 to 0.55, and Georgia from 0.24 to 0.55 during 1995–2015. These countries had an average urbanization rate of 74%, 68%, and 54% during 1995–2015, respectively. The BRI can accelerate the urbanization process by the provision of new buildings and infrastructure construction, trade and foreign investment, which seems to increase energy consumption directly. However, accelerating urbanization may improve energy efficiency by indirect means. In already highly urbanized areas, the construction sector uses energy more efficiently because of its more mature or advanced technology and greater focus on green buildings. The scale effect stimulated by urbanization motivates the decrease in unit resource costs because of a large-scale production pattern. Income improvement induced from urbanization also raises the people's demand for a cleaner environment, which can cause the imposition of stricter domestic regulations to improve energy efficiency. In addition, urbanization leads to an energy transition to cleaner and more effective electricity and natural gas. Moreover, transportation tends to be more energy efficient in highly urbanized areas, as higher density areas often have a relatively higher number of public transport users, whereas residents in low-density areas are much more dependent on private vehicles than those living in the city center [68].
(2) Their economic structure transitions from energy-intensive *industrial* activities to less energy-intensive *service* activities. Countries such as the Czech Republic and Latvia with a higher TFEE growth rate, had a declining industry share from 40% to 36%, and 30% to 22% respectively during 1995–2015. This transition reduced the amount of energy required per unit GDP for the economy as a whole [69]. They also make their energy consumption structure cleaner, which is helpful for more efficient energy utilization. Such backward countries with a greater TFEE growth rate as Mongolia and Moldova, improved their no-coal consumption from 0.17 in 1996 to 0.31 in 2015, and 0.87 in 1996 to 0.97 in 2015.
(3) That they make great technological breakthroughs or progress, which may come from technology diffusion through larger scale trade or FDI caused by BRI, thus improving their end-use efficiency or fuel conversion efficiency to reduce energy input when there is equal capital, labor input and output, or raise output in the case of equal capital, labor or energy input, relying on technological progress [16]. Consequently, the backward countries with a higher TFEE growth rate caused by accelerated urbanization, a larger share of service industry, cleaner energy structure, and technology progress are catching-up with the frontier countries at a faster rate of convergence. Therefore, the TFEE convergence rate is increasing with the increase in TFEE growth rate.

In contrast, backward countries with a smaller or negative TFEE growth rate have a smaller, even non-significant, convergence rate. In particular, as discussed in the previous section, TFEE is generally greater in relatively high-income countries, so the TFEE gap is narrow between high-income and frontier countries. In Greece, for instance, the average TFEE in 1995–2015 was around 0.98, and reached 1 in many years, i.e., the frontier level. The catch-up process for high-income countries is difficult unless they make abrupt technological breakthroughs or their economy is growing rapidly. Thus, when TFEE growth is very small in high-income countries, there seems to be little catch-up effect, and when TFEE growth is negative, the convergence rate is not significant.

That the TFEE in high-income BRI countries converges at a faster rate than their low-income equivalents when TFEE growth rate is greater, may be because the TFEE level in relatively high-income countries is generally better. The TFEE gap between high-income and frontier countries is also quite narrow due to their greater economic development, advanced technology or management, low share of energy-intensive industry, more clean energy utilization, higher urbanization, etc. Relatively high- and low-income counties had an average TFEE of 0.67 and 0.40 respectively in the sample period. Therefore, relatively high-income countries with greater TFEE growth overcome the difficult task of greatly improving their already high TFEE by having a good economic foundation or making technological breakthroughs; relatively low-income countries, on the other hand, may have a relatively long way to catch up with frontier countries because of their originally low TFEE. As a result, it takes a shorter time for high-income countries to catch up with frontier countries, and the convergence rate is faster than low-income countries.

The reason why the TFEE convergence rate in Eastern Europe and West Asia countries is faster than Central and Eastern Asia countries mainly lies in the greater TFEE growth in Eastern Europe and West Asia countries. For example, we find most countries of the top 30 countries with greater TFEE growth rate are located in the Eastern Europe and West Asia. As discussed, countries with a greater TFEE growth rate tend to have the characteristics of urbanization acceleration, economic structure transitions, cleaner energy consumption structure, and making great technological breakthroughs or progress. Hence, compared with Central and Eastern Asia countries, the backward countries in Eastern Europe and West Asia with a low initial TFEE can catch up with the frontier faster than the backward countries in Central and Eastern Asia.

Regarding the generally constrained effect of R&D investment on TFEE convergence, this is partly due to the countries' characteristics of inadequate innovation ability and weak R&D absorption capacity, especially in low-income countries, which results in domestic companies failing to absorb advanced technologies effectively from FDI and trade. Moreover, advanced countries with a higher TFEE have a cumulative advantage; most of the world's R&D investment - approximately 70% of the global total - is from high-income countries [70][6]. Generally, countries with higher energy efficiency have more advanced technology, with better R&D innovation capacity and absorption capacity, while a weak innovation capacity and absorption capacity in BRI countries with low energy efficiency render them unable to generate innovation effectively. Instead, it may cause the outflow of talent because of the competitive treatment of foreign companies, which leads to technology diffusion to foreign countries. It is not beneficial to narrow the technology gap and TFEE convergence of BRI countries. This result demonstrates the need to enhance that innovation capacity and absorption capacity of R&D, especially in low-income BRI

[6] http://www.wipo.int/edocs/pubdocs/en/intproperty/944/wipo_pub_944_2011.pdf.

countries. Compared with FDI, the R&D capacity for absorbing trade technology diffusion is much better, because foreign companies keep their core technologies, while domestic companies find it difficult to obtain advanced technologies from foreign companies.

7. Conclusions and policy implications

This paper uses panel quantile regression to investigate the comparative 1995–2015 TFEE conditional β-convergence for 60 BRI countries, as well as the main influencing factors involved. The main results are that, in general, the TFEE of the 60 BRI countries converge to their own steady state or to EU-15 when their TFEE growth rate is greater. In addition, the TFEE catch-up rate increases with the increase in TFEE growth rate. Moreover, the TFEE in high-income BRI countries converges at a faster rate than that of low-income BRI countries when the TFEE growth rate is greater. Furthermore, the TFEE convergence rate in Eastern Europe and West Asia countries is faster than Central and Eastern Asia countries. Finally, the R&D investment of BRI countries decelerates the TFEE convergence rate where there is weak innovation capability and absorption capability, especially in less developed BRI countries, while other economic, structure, and technology factors do not significantly affect the TFEE convergence of BRI countries.

Regarding the TFEE, there is a gap between the BRI countries and the developed EU-15 countries. The Middle East and West Asia has the highest average annual TFEE, followed by Southeast Asia, Central and Eastern Europe, China, South Asia, Russia and Mongolia, and Central Asia. Countries with a more advanced economy have a higher level of TFEE generally. Moreover, the global finance crisis declined the TFEE in BRI countries, with the annual average increasing before 2009, then decreasing, and slowly increasing after 2010.

The results of the study suggest three main policy implications:

(1) BRI countries, whether relatively high- or low-income, need to balance their economic development and energy conservation to dramatically increase their TFEE, which can lead to significant TFEE convergence in countries with lower initial TFEE, compared with more advanced countries such as European Union; and the greater the TFEE growth, the faster is the TFEE catch-up rate. Increasing the urbanization rate and cleaner energy consumption may be effective ways of doing this for BRI countries. China can help by focusing on cooperation in promoting the BRI countries' urbanization and renewable energy development to improve their energy efficiency effectively.
(2) High-income BRI countries need to pay more attention to the degree of their TFEE growth, because TFEE may not converge with more advanced economies when its growth is low. There is much room for improvement of the TFEE of low-income BRI countries, which need to improve their TFEE to catch up with countries with a higher level of TFEE.
(3) Compared with countries in Eastern Europe and West Asia, the backward countries in Central and Eastern Asia need to facilitate their energy efficiency growth rate to increase their catch-up rate with frontier countries. They should enforce energy efficiency to get rid of stagnation or even negative improvement, which can be through the urbanization process, a less energy-intensive industry transition, cleaner energy structure, and greater technological progress.
(4) There may be a big gap in R&D innovation capability between low-income BRI countries and high-income countries. Low-income BRI countries, however, need to pay more attention to improving their capability of absorbing technology diffusion from FDI and trade to narrow the technology gap and accelerate TFEE convergence.

There are several opportunities for future research. For instance, China intends to achieve a 'win-win' situation by cooperation with BRI countries in production capacity. With the increasing trade and investment between China and BRI countries, the influence of trade or investment on energy efficiency convergence is worthy of further study. That these influences may be heterogeneous, because of the heterogeneity of economic development and energy use in the countries, is also a key issue in need of further examination.

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