Factors influencing embodied energy trade between the Belt and Road countries: a gravity approach

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Abstract
Against the backdrop of current global collaboration on mitigating carbon emissions, how to reduce the energy uses in the Belt and Road Initiative area becomes an urgent and big challenge facing the global community. Using the Eora input-output database, this paper accounts the embodied energy trade between Belt and Road countries in 2015, followed by an investigation of the factors influencing the embodied energy trade through a panel gravity model. Global value chain participation and position are two newly considered factors in analyzing the determinants of embodied energy flow. We find that the main bilateral embodied flow paths are from South Korea to China, China to South Korea, Singapore to China, Ukraine to Russia, and Malaysia to Singapore. Five percent embodied energy flow paths account for 80% of the total bilateral embodied energy flow volume between Belt and Road countries. The gravity model results indicate that gross domestic product (GDP) per capita, population, global value chain participation are the key drivers of bilateral embodied energy trade, while the industrial share of GDP and global value chain position are negatively related to the trade. Energy intensity plays a crucial role in reducing the bilateral embodied energy flow. These results are useful in the policymaking of sustainable development for the Belt and Road Initiative.

Keywords  Embodied energy · Gravity model · Input-output analysis · Belt and Road Initiative · Global value chain

Introduction
As a new international development initiative, Belt and Road Initiative (BRI), covering more than 60 economies and 60% of the global population, has attracted worldwide academic interests (Cheng and Ge 2020). It is reported that the BRI has contributed less than 30% of global gross domestic product (GDP) at the expense of almost 50% of the world’s primary energy consumption, and their energy consumption and carbon emissions per unit GDP are 50% higher than the global average (Qi et al. 2019). Moreover, fossil energy dominates the energy mix of most BRI countries (Nibedita and Irfan 2021). Against the backdrop of current global collaboration on mitigating carbon emissions, how to reduce the energy uses in the BRI area becomes an urgent and big challenge facing the global community. A key preliminary step to address this issue is to understand the energy use patterns of BRI countries and the factors influencing the energy trade between BRI countries.

Currently, most energy reduction efforts focus on controlling the direct energy used domestically, ignoring the substantial indirect energy uses along the whole globally distributed production chain (Cortes-Borda et al. 2015; Shi et al. 2017). It has been revealed that such local ignorance leads to a global undesirable outcome (Peters and Hertwich 2008). If countries aim to achieve the energy conservation through controlling the direct energy consumption, they incline to do this by transferring energy-intensive industries to other regions and meanwhile importing from abroad the finished goods or energy-intensive intermediate goods (Chen et al. 2018; Wiedmann and Lenzen 2018; Wu and Chen 2017). Ultimately such local favorable actions lead to a global unfavorable outcome in terms of worldwide energy reduction and carbon mitigation (Guo et al. 2021). This phenomenon leads to essential changes in trade relations and energy use and makes it necessary to analyze the energy use profiles from a systemic perspective.
and evaluate it within a globally integrated framework (Camacho et al. 2021).

From a systemic perspective, each BRI country makes use of its competitive advantages and participates in the global value chains (GVCs) that are characterized by long and complex supply relations (Aslam et al. 2017; Backer and Miroudot 2013). Meanwhile, energy is an indispensable input for production activities, and it is embodied in the traded intermediate and final goods and services (Brown and Herendeen 1996; Costanza 1980; Sun et al. 2016; Wang et al. 2020b). To aggregate the energy uses along the globally distributed supply chains, globally integrated frameworks have thus been proposed (Miller and Blair 2009). Among them, the global embodied energy accounting framework, which is based on the multi-regional input-output (MRIO) model, is widely adopted due to its ability to trace the total energy flows across sectors and regions and to reveal indirect energy uses along the whole globally distributed production chain (Chen and Chen 2011, 2013). Therefore, this paper adopts the embodied energy accounting framework to evaluate the energy use and identify features of energy trade among the BRI countries.

Further, to analyze the drivers of embodied energy flow in MRIO model, scholars usually adopt structural decomposition analysis (SDA) method, since the MRIO-based SDA studies can reveal the indirect effect and tell apart the technological effect and final demand effect on the energy change (Feng et al. 2012; Su and Ang 2012). Earlier studies are featured by three-factor analysis, including intensity effects, intermediate structural effects, and final demand effects (Tao et al. 2018). These three factors are further decomposed by later studies (Jiang et al. 2021; Lam et al. 2019; Lan et al. 2016; Meng et al. 2019; Wang and Han 2021; Wang and Liu 2021; Wang et al. 2020b; Xie 2014; Zhao et al. 2018). Nonetheless, SDA still lacks a relatively flexible modelization of qualitative factors, and thus its flexibility is limited (Wang et al. 2017). Furthermore, SDA approach focuses on the home country analysis rather than edge analysis and thus ignores the influences of reciprocal economic factors on the bilateral embodied energy flow, such as the spatial character of trade flows and country/time-specific variables. Accordingly, combining MRIO with traditional gravity model is proposed to avoid this limitation (Duarte et al. 2018).

Among the country-specific variables, the GVC-related factors with few empirical tests deserve further attention. As noted previously, world trade and production are increasingly structured around GVCs, and such international fragmentation of production leads to embodied energy flow in the global production network (Chen et al. 2018; Chen and Chen 2013; Shi et al. 2017). Therefore, the extent to which a country is involved in the GVCs and the position a country occupies in the GVCs imply different patterns and intensities of energy consumption, and thus are expected to influence the embodied energy flow. Ignoring them will limit the understanding of actual drivers of embodied energy flow and consequently create obstacles for policy practices to achieve the expected outcomes. To fill this gap, we construct a panel gravity model to examine the reciprocal influences of these important factors and other conventional factors on the bilateral embodied energy trade.

To sum up, there are two main contributions of this paper to the literature. Firstly, we evaluate the energy use and uncover the main features of energy trade among BRI countries from a systemic perspective by adopting the embodied energy accounting framework. This work enriches the embodied energy studies at the super-national scale and among developing economies. Secondly, by constructing a gravity model and using panel data analysis, we highlight the impact of countries’ positions in the global supply chains and the influence of countries’ GVC participations on bilateral embodied energy trade between BRI countries, which deepens the understanding on the factors driving the embodied energy trade.

The rest of this paper is organized as follows: Sect. 2 is the literature review, Sect. 3 presents the accounting method for embodied energy, the gravity model of bilateral embodied energy trade, and data required for accounting and econometric analysis. Section 4 displays the main results and discussions. Section 5 is the concluding remarks and policy implications.

**Literature review**

**A brief overview of studies related to embodied energy flow**

Direct energy flow is relatively easier to measure than the indirect energy flow. To assess the indirect energy use embodied in the traded goods production, one can resort to the concept of embodied energy originated from the combination of system ecology and input-output analysis (Brown and Herendeen 1996). Embodied energy is the direct and indirect energy totally required to produce goods and services (Bullard and Herendeen 1975; Costanza 1980), recording on-site and off-site energy consumption of productions and thus providing a more systematic perspective of energy use (Chen and Chen 2013). Because of this property of capturing the full spectrum of energy use, embodied energy flows at different scales have been widely investigated.

At the inter-provincial and urban scale, many studies are about China due to its rich and complex internal economic diversities. Zhang et al. (2016) explores the temporal and spatial changes of embodied energy transfers via China’s domestic trade over 2002–2007, Chen et al. (2017) investigates the transfer of embodied energy between the Jing-Jin-Ji area and other provinces in China, and Gao et al. (2018) reveals the network structure of inter-provincial transfer of embodied
primary energy in China. To comprehensively understand and identify the underlying drivers behind the embodied energy flows, Gao et al. (2018) considers coal, oil, natural gas, and non-fossil fuels, and includes international import and export in the calculation of embodied energy inflows and outflows between China’s provinces, i.e., combining the world input-output table with China’s inter-provincial input-output table together. Guo et al. (2020) depicts the internal and external embodied energy flows in the Jing-Jin-Ji, Yangtze-River-Delta, and Pearl-River-Delta and analyzes their embodied energy transfer patterns.

Bilateral trade is a classic research topic in the international trade. Especially when scholars notice that most global trade volume occurs between several economies (Serrano and Boguñá 2003; Shi et al. 2017), accounting energy use embodied in the critical bilateral trade relations attracts attention. For example, Yang et al. (2014) calculates the energy embodied in the import and export between China and America to verify the real energy flows in the Sino-USA trade, and Zhu et al. (2020) analyzes the share of China’s embodied energy in the exports with major trading partners during the period of 2005–2015 and the forces driving the varied structure of shares. Tian et al. (2017) accounts the resources footprints embodied in the China-EU 27 countries trade. Zhang et al. (2021) reveals the embodied energy in the export flows of China along the global value chain.

With more global MRIO data and energy use data available and increasing importance of worldwide energy conservation, embodied energy flow research at the global scale has become a hot topic in recent years. At the global level, Chen and Chen (2013) presents a network simulation of the global embodied energy flows in 2007, Cortes-Borda et al. (2015) explores the solar energy embodied in the international trade of goods and services, Shi et al. (2017) and Sun (2018) study the evolutionary features of global embodied energy flow network through the combination of multi-regional input-output (MRIO) analysis and complex network analysis, Wu and Chen et al. (2017) traces the embodied energy flow in the global supply chains, and Chen et al. (2018) uncovers the structure of global embodied energy flow network. Zhang et al. (2019) comprehensively evaluates the embodied energy, carbon emission, and value-added flows in the BRICS’ trade. Jiang et al. (2020) analyzes the spatial patterns of embodied energy trade between 39 countries and identifies the driving factors of embodied energy use with LMDI method. Given the increasing importance of natural gas in mitigating carbon emission, Kan et al. (2020) studies the evolution of natural gas uses across global supply chains in the period of 2000–2011. Shepard and Pratson (2020) constructs a hybrid input-output model to study the indirect energy flows through global trade and obtains that 23% of embodied energy trade occurs between countries with no direct energy linkage. Song et al. (2021) compares the network features of global direct crude oil trade with that of the embodied oil trade.

**Brief review of recent studies combining gravity model and MRIO model**

The prosperity of trade is accompanied by the transfer of resources/pollutants from the demand side to the supply side. To identify the determinants of resource and environmental issues embodied in trade, scholars have begun to combine the gravity model and the MRIO model, since gravity model has a high explanatory power for bilateral interactions and MRIO model can capture the complete resources/pollutions flow embodied in trade. Among these academic explorations, Fracasso (2014) examines the factors influencing water use embodied in the global agricultural goods trade. Combining MRIO with trade gravity panel data analysis, Duarte et al. (2018) studies the determinants of carbon embodied in world trade during a period of 15 years. Duarte et al. (2019) uses the data of 1965–2010 to examine long-term drivers of the global virtual water trade. Islam et al. (2019) investigates the impact of tariff reduction on the carbon emissions embodied in the imports of G20 economies. Including population, economic development, coal consumption, distance, and environmental regulations into a gravity model, Wang et al. (2019) assesses the factors affecting the SO₂ emissions embodied in the domestic trade of China. On the one hand, these studies show the usefulness of combining the gravity model and the MRIO model. On the other hand, the previous studies in this field pay less attention on the GVC-related factors in identifying the determinants of resource and environmental issues embodied in trade, which can be improved. One of the main contributions of this paper is including GVC-related factors into the gravity model to quantify the factors influencing embodied energy flow more comprehensively between BRI countries.

**Materials and methods**

**Embodied energy flow accounting**

In literature, there are two approaches to account the energy/emission embodied in trade, i.e., energy/emission embodied in bilateral trade (EEBT) approach and MRIO approach (Peters 2008; Wiedmann et al. 2007). EEBT approach applies a single-region input-output (SROI) model to each entity and calculates the energy/emission embodied in an entity’s imports as the sum of all other countries’ energy/emissions embodied in their exports to the country; however, the MRIO approach applies the full MRIO model to all entities and differs the imported products for intermediate consumption from the ones for final demand (Su and Ang 2011). BRI is a multilateral initiative and an inter-regional production system, and
thus adopting the MRIO approach is a more appropriate way to account for the inter-regional feedback effects (Peters 2008), although this may involve uncertainties from aggregation issues (Su and Ang 2011).

Our first step is to account the global embodied energy flow using the full global Eora database and then extract the BRI embodied energy flow from the global embodied energy trade. The accounting method applied in this paper is based on Chen and Chen (2013) and Sun et al. (2016). The equation of embodied energy flow balance for a single industry in an individual region is expressed by Eq. (1):

$$ d_i^r \times \sum_{s=1}^{m} \omega_j^r = \omega_i^r \times \left( \sum_{s=1}^{m} \sum_{j=1}^{n} z_{ij}^r + \sum_{s=1}^{m} \gamma_{is}^r \right) $$  \hspace{1cm} (1)

where $d_i^r$ denotes the direct energy input of sector $i$ of region $r$, $c_{ij}^r$ the intermediate use of goods by sector $i$ of region $r$ that is produced by sector $j$ of region $s$, $\omega_j^r$ the embodied energy intensity of sector $j$ of region $s$, and $y_{rs}^r$ is the final demand of region $s$ that is supplied by sector $i$ of region $r$. $m$ denotes the number of regions, and $n$ denotes the number of sectors.

The MRIO model in the matrix is expressed by Eq. (2):

$$ D + WZ = WX $$  \hspace{1cm} (2)

where $D = [d_1^r \ d_2^r \ \cdots \ d_m^r]$ is the vector of sectoral direct energy input, $Z=\begin{bmatrix} z_{11}^r & z_{12}^r & \cdots & z_{1m}^r \\ z_{21}^r & z_{22}^r & \cdots & z_{2m}^r \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1}^r & z_{m2}^r & \cdots & z_{mm}^r \end{bmatrix}$ is the intermediate matrix, $Y=\begin{bmatrix} y_{11}^r & y_{12}^r & \cdots & y_{1m}^r \\ y_{21}^r & y_{22}^r & \cdots & y_{2m}^r \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1}^r & y_{m2}^r & \cdots & y_{mm}^r \end{bmatrix}$ is the final demand matrix, $W=\begin{bmatrix} \omega_1^r \\ \omega_2^r \\ \vdots \\ \omega_n^r \end{bmatrix}$ is the vector of sectoral embodied energy intensity, and $X = \begin{bmatrix} \sum_{j=1}^{n} \sum_{i=1}^{m} \omega_i^r z_{ij}^r + \sum_{j=1}^{m} \gamma_{is}^r \\ 0 \\ \vdots \\ 0 \\ \sum_{j=1}^{n} \sum_{i=1}^{m} \omega_i^r z_{ij}^r + \sum_{j=1}^{m} \gamma_{is}^r \\ \vdots \\ \sum_{j=1}^{n} \sum_{i=1}^{m} \omega_i^r z_{ij}^r + \sum_{j=1}^{m} \gamma_{is}^r \\ 0 \end{bmatrix}$ is the diagonal matrix of total output.

Rewriting Eq. (2), we have the vector of sectoral embodied energy intensity, see Eq. (3):

$$ W = D(X-Z)^{-1} $$  \hspace{1cm} (3)

Since the technical matrix $A = ZX^{-1}$ and the vector of sectoral direct energy intensity $E = DX^{-1}$, Eq. (3) is rewritten as Eq. (4):

$$ W = E(I-A)^{-1} $$  \hspace{1cm} (4)

where $(I-A)^{-1}$ is called the Leontief inverse matrix and $I$ is the identity matrix.

With the input-output data and direct energy input data, once obtained the vector of sectoral embodied energy intensity $W$, multiplying $Z$ with $\tilde{W}$, the diagonal matrix of $W$, we then obtain the energy flow embodied in the intermediate matrix $G$, see Eq. (5):

$$ G = \tilde{W}Z = \begin{bmatrix} g_{11}^r & \cdots & g_{1m}^r \\ g_{21}^r & \cdots & g_{2m}^r \\ \vdots & \ddots & \vdots \\ g_{m1}^r & \cdots & g_{mm}^r \end{bmatrix} $$  \hspace{1cm} (5)

where $g_{ij}^r$ denotes the embodied energy flow from sector $i$ of region $r$ to sector $j$ of region $s$.

Multiplying $\tilde{W}$ with the final demand matrix $Y$, we obtain the energy embodied in the final demand matrix $H$:

$$ H = \tilde{W}Y = \begin{bmatrix} h_{11}^r \\ \vdots \\ h_{m1}^r \\ h_{n1}^r \end{bmatrix} $$  \hspace{1cm} (6)

Based on Eqs. (5) and (6), merging all sectors, i.e., $c_{rs}^r = \sum_{i=1}^{m} \sum_{j=1}^{n} g_{ij}^r z_{is}^r + \sum_{i=1}^{m} h_{ir}^r$, we obtain the embodied energy flow between countries, see Eq. (7):

$$ C = \begin{bmatrix} c_{11} & \cdots & c_{1m} \\ c_{21} & \cdots & c_{2m} \\ \vdots & \ddots & \vdots \\ c_{m1} & \cdots & c_{mm} \end{bmatrix} $$  \hspace{1cm} (7)

The energy embodied in the region $r$’s import of intermediate goods is expressed by Eq. (8):

$$ \text{TEIM}_r = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{s=1}^{m} c_{rs}^r z_{ij}^s $$  \hspace{1cm} (8)

The energy embodied in the region $r$’s export of intermediate goods is expressed by Eq. (9):

$$ \text{TEEX}_r = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{s=1}^{m} c_{is}^r z_{ij}^s $$  \hspace{1cm} (9)

The net energy exports embodied in the intermediate goods of region $r$ are expressed by Eq. (10):

$$ \text{NEXX}_r = \text{TEEX}_r - \text{TEIM}_r $$  \hspace{1cm} (10)

The energy embodied in the region $r$’s import of final goods is expressed by Eq. (11):

$$ \text{FEIM}_r = \sum_{i=1}^{m} \sum_{j=1}^{n} \omega_i^r y_{ij}^r $$  \hspace{1cm} (11)

The energy embodied in the region $r$’s export of final goods is expressed by Eq. (12):

$$ \text{FEEX}_r = \sum_{i=1}^{m} \sum_{j=1}^{n} \omega_i^r y_{ij}^r $$  \hspace{1cm} (12)
The net energy exports embodied in the final goods of region \( r \) are expressed by Eq. (13):

\[
\text{NEXF}_r = \text{FEEX}_r' - \text{FEIM}_r'.
\] (13)

Gravity model

The gravity model was firstly adopted by Nobel Laureate J. Tinbergen (Tinbergen 1962), who described the bilateral trade flows between two countries as the function of economic sizes and the distance between them. Gravity model is now a well-grounded model in mainstream economics (Anderson 1979; Anderson and van Wincoop 2003; Bergstrand 1985, 1989; Chaney 2018). Among empirical studies, the impact of GDP per capita, population, and geographical distance on the embodied energy trade have been quantified.

Following the previous research, we examine the impact of GDP per capita, population, and geographical distance on the embodied energy trade between BRI countries, too. Besides these factors, we also consider the impact of energy intensity and industrial structure, since these two factors have critical influences on the energy consumption (Wang et al. 2014).

More importantly, we contribute to the gravity model by adding two GVC-related factors to identify the determinants of resource and environmental issues embodied in trade. The first one is the GVC participation index that simultaneously considers one country’s backward participation and forward participation in the GVCs. The larger the index, the greater the intensity of involvement of a particular country in GVCs (Aslam et al. 2017). Theoretically, greater involvement in GVCs will lead to more bilateral embodied energy trade. The second one is the GVC position index that characterizes the relative upstreamness of a country in GVC (Aslam et al. 2017). A larger position index means relatively more upstream, and smaller corresponds to more downstream. Theoretically, upstream countries tend to export direct energy use, and downstream tend to have more indirect energy trade.

Considering all these factors, we construct an extended gravity model as Eq. (14) to examine their impacts on the bilateral embodied energy flow between BRI countries.

\[
\ln(c_{rst}) = \ln(GDPP_{rt}) + \ln(GDPP_{st}) + \ln(POP_{rt}) + \ln(POP_{st}) + \ln(GDrs) + \ln(GVCP_{rt}) + \ln(GVCP_{st}) + \ln(IND_{rt}) + \ln(IND_{st}) + \ln(EI_{rt}) + \ln(EI_{st}) + \varepsilon_{rst}
\]

(14)

where \( c_{rst} \) denotes the bilateral embodied energy flow between country \( r \) and \( s \) in \( t \) year; \( K \) is the constant variable; \( GDPP_{rt} \) is the GDP per capita of country \( r \) in \( t \) year; \( POP_{rt} \) is the population of \( r \) in \( t \) year; \( GDrs \) is the geographical distance between \( r \) and \( s \), measured by the range between the capital city of trading partners; \( POS_{rt} \) is the GVC position of \( r \) in \( t \) year; \( GVCP_{rt} \) is the GVC participation of \( r \) in \( t \) year; \( IND_{rt} \) is the industrial share of GDP of \( r \) in \( t \) year; \( EI_{rt} \) is the direct energy intensity of country \( r \) in \( t \) year; and \( \varepsilon_{rst} \) is the residual term. \( \beta_i \) can be interpreted as the elasticity of variable \( i \).

Data source

There are several worldwide input-output databases for MROI studies, such as GTAP, WIOD, EXIOBASE, and Eora. Among them, GTAP covers 121 economies and updates to 2014, WIOD covers 41 regions and updates to 2014, EXIOBASE covers 44 economies and updates to 2011. Eora input-output database covers 190 economies and updates to 2015. Furthermore, most BRI countries are covered in the Eora database. The coverage and timeliness of the Eora make it fit this study best. The input-output data, energy use by sector, industry share of GDP are from Eora (Lenzen et al. 2012; Lenzen et al. 2013), which has a resolution of 26 sectors. Until March 2018, there were 72 BRI countries listed on the official BRI website (www.yidaiyilu.gov.cn). However, the input-output data for East Timor and Palestine are not available in Eora (version v 199.82). Therefore, only 70 BRI countries listed in Table 5 are included in this study.

GDP per capita, population, and energy intensity (mega Joule per GDP) are from the World Development Indicators of World Bank; GVC participation index and position index data are from the global value chain dataset of Eora; and geographic distance (kilometers) is available at CEPII (Mayer and Zignago 2012). Fossil energy trade data are from the UN Comtrade database. Since the time series data of all these variables for BRI countries are from 2002 to 2015, Eora has been widely used in the time series studies of energy and energy-related carbon emissions. For example, Lan et al. (2016) quantified drivers for changes in global energy footprints from 1990 to 2010. Han et al. (2020b) comprehensively analyzed the carbon inequality and regional development and compared the carbon emissions in and outside the Belt and Road area from 1990 to 2015. Onat and Kucukvar (2020) conducted a time series analysis of construction industries’ carbon emissions from1995 to 2012. Wang et al. (2020a) evaluated the environmental performances of global supply chains in manufacturing sectors from 2005 to 2014. Li et al. (2021) analyzed evolution of the global oil supply chain using the Eora database from 2000 to 2015. Energy consumption data are usually used in environmental input-output analysis, which may suffer from the updating frequency of energy dataset. Some efforts are made to address this time-lag issue by adopting system input-output analysis approach and using energy exploration data from IEA, see Li et al. (2021) for instance and more methodology discussions in Chen and Wu (2017). Unfortunately, their energy/emission datasets are not directly shared in their publications. Sharing more information could promote relevant studies.
therefore, the timespan for the empirical gravity analysis is from 2002 to 2015. The number of total observations is 56,448.

**Empirical results and discussions**

**Embodied energy trade between BRI countries**

Fossil energy is the primary power source to support the economy, and its distribution is uneven. International fossil energy trade reveals the first-order feature of the global energy production and consumption. However, fossil energy trade does not capture the full spectrum of energy consumption. In the era of globalization, production processes are sliced up and international trade develops rapidly, especially intermediate goods trade, leading to the international transfer of energy embodied in the goods (Chen et al. 2018; Chen and Wu 2017). Furthermore, increasing countries attempt to outsource energy-intensive industries and import finished products to avoid environmental pollution associated with production (Wiedmann and Lenzen 2018). Embodied energy thus captures the second-order and high-order feature of the energy transfer among economies. Comparing the direct fossil energy trade feature and the embodied energy trade feature, therefore, reveals more information for policymakers.

Major and active countries in the BRI embodied energy trade are presented in Fig. 1. Three communities are detected in the BRI embodied trade. China, South Korea, Singapore, Indonesia, Thailand, and Vietnam are in the same community. Russia and other East European countries form the second cluster. India, Turkey, Saudi Arabia, and UAE form the third cluster. China (exporting 4.68E+09 TJ), South Korea (3.46E+09 TJ), Singapore (2.99E+09 TJ), Russia (1.90E+09 TJ), and Malaysia (1.89E+09 TJ) are the top 5 exporters, while China (importing 5.45E+09 TJ), South Korea (2.48E+09 TJ), Russia (2.32E+09 TJ), Singapore (1.98E+09 TJ), and Turkey (1.83E+09 TJ) are the top 5 importers. In terms of the net embodied energy trade, Singapore, South Korea, Malaysia, United Arab Emirates (UAE), and Ukraine are the first 5 net exporters, while China, Turkey, Russia, Poland, and Philippines are the top 5 net importers among BRI countries.

*Note:* We plot this embodied energy flow figure using 525 flow paths that account for 90% of the total flow volume. The font size and the size of the node denote the magnitude of the outflows of a country’s embodied energy. The color shows the communities within which close embodied energy trade occurs. The community detection is done by Gephi, a software for visualization.

In this study, we find that China is an embodied energy net exporter in BRI, which is different from previous study conducted by Han et al. (2020a). The position of China as an embodied energy net exporter or importer is determined by the geographic coverage of dataset. China indeed is always regarded as embodied energy exporter in the global embodied energy calculation, and it is shown by Han et al. (2020a) that China is also an embodied energy exporter in BRI. However, we must notice that BRI is a dynamic concept. The member countries joining the initiative increase as time goes by. Han et al. (2020a) uses 65 countries as BRI countries for their analysis, while we use 70 countries. Therefore, there is an opposite result due to the different geographic coverage.

It is also interesting to find that Singapore is shown as an embodied energy net exporter in the results, which is well-known as a country highly relied on the direct energy import. Because of its limited energy resources, Singapore imports direct energy for production, such as crude oil, natural gas, and so on. In this sense, Singapore is a direct energy importer. From the perspective of embodied energy, however, Singapore is an embodied energy net exporter. Due to its limited domestic market, Singapore produces goods largely for meeting foreign demand, either for intermediate goods demand or final demand overseas. Singaporean open economy is well-known for its success, and the reason behind this is its net export. In terms of embodied energy terms, Singapore is shown as an embodied energy net exporter. Fig. 3 in Sect. 3.2 also shows that Singapore net exports more embodied energy in the final uses than the embodied energy in the intermediate uses.

The main bilateral embodied energy flow paths are South Korea → China (1.88E+09 TJ), China → South Korea (9.25E+08 TJ), Singapore → China (7.38E+08 TJ), Ukraine → Russia (6.71E+08 TJ), Malaysia → Singapore (6.02E+08 TJ), Malaysia → China (5.21E+08 TJ), Singapore → Malaysia (4.78E+08 TJ), South Korea → Turkey (4.35E+08 TJ), and Turkey → China (4.15E+08 TJ).
TJ), Singapore → Indonesia (4.23E+08 TJ), and Russia → China (3.96E+08 TJ). These 10 embodied energy flow paths carry 22% of bilateral embodied energy flow volume between BRI countries. The 5% embodied energy flow paths (top 250 flow paths) account for 80% of the total bilateral embodied energy flow volume, and the 10% paths (top 500) account for 90% of the total bilateral embodied energy flow volume.

In their investigations on the global energy flow embodied in international trade through the MRIO-based network model, Shi et al. (2017) and Chen et al. (2018) uncover the scale-free property of the global embodied energy flow network. The distribution of embodied energy flow between BRI countries follows a power law distribution (few flow paths account for most flow volume) and also shows the scale-free property as the global embodied energy network does. Additionally, different from its role as the largest net embodied energy exporter at global level (Chen and Chen 2011), China is the biggest net importers of embodied energy in Belt and Road area.

The trade feature of embodied energy and that of direct fossil energy is strikingly different (see Figs. 1 and 2). Combining coal, oil, and gas as the fossil energy flow, we find that Russia, Indonesia, Saudi Arabia, Qatar, and UAE are the major exporters, while China, India, South Korea, Singapore, and Thailand are the major importers. In terms of net fossil energy trade, Russia, Saudi Arabia, Indonesia, Qatar, and Iraq are the top 5 net exporters, while China, India, South Korea, Thailand, and Singapore are the first 5 net importers.

Note: We plot a fossil energy trade using 160 paths that account for 90% of the total fossil energy flow volume. The font size and the size of the node denote the magnitude of the outflows of a country’s direct fossil energy. The color shows the communities within which close fossil energy trade occurs.

The main bilateral fossil energy flows are Indonesia → India (3.46E+06 TJ), Russia → China (2.52E+06 TJ), Indonesia → China (2.43E+06 TJ), Saudi Arabia → China (2.27E+06 TJ), Saudi Arabia → South Korea (2.00E+06 TJ), Russia → Belarus (1.95E+06 TJ), Saudi Arabia → India (1.85E+06 TJ), Qatar → South Korea (1.79E+06 TJ), Russia → South Korea (1.64E+06 TJ), and Iraq → India (1.42E+06 TJ). These 10 energy flow paths carry 28% of bilateral energy flow volume between BRI countries. The 5% fossil energy flow paths (top 99 flow paths) account for 84% of the total bilateral embodied energy flow volume, and the 10% paths (top 198) account for 93% of the total bilateral embodied energy flow volume, which also shows the scale-free property.

The comparison between the embodied energy trade and the fossil energy trade demonstrates that the embodied energy trade is less concentrated than the fossil energy trade. Natural resource endowments determine the flow directions of fossil energy trade. Different from this, comparative advantages over labor, capital, and institutional factor influencing their participations and positions in the global value chains determine the flow directions of embodied energy trade, which will be further analyzed in Sect. 4.3.

The comparison between the embodied energy trade and the fossil energy trade also highlights that China is a major net importer of the fossil energy and of the embodied energy among BRI countries. China is exposed to double risks of energy dependence. Therefore, it is important for China to establish good relations not only with countries of rich energy endowments like Russia and Saudi Arabia but also with countries of big net embodied energy exports like South Korea and Singapore. As major energy importers, on one hand, South Korea and Singapore are significantly affected by the price fluctuations of primary energy sources; on the other hand, as big embodied energy exporters, they exert pressure on the local environment through producing intermediate goods and final products. The continuous energy-saving efforts of South Korea and Singapore thus can reduce the impact of exogenous price shocks on their economy and achieve sustainable development.

Table 1 presents the top 10 cross-border embodied energy flows between sectors, accounting for 0.003% of all flow paths but carrying 10% of embodied energy flow volume. These major flows occur between the same sector of different countries, especially the Electrical and Machinery sector, which reveals that the production process of the Electrical and Machinery sector is sliced and geo-diversified. The intermediate goods trade of Electrical and Machinery sector occurs mainly in East Asia and Southeast Asia countries.
China’s *Electrical and Machinery* sector plays a key role in the above-mentioned major flows. As Zhu et al. (2020) reports, *Computer, electronic and optical products* sector and *Electrical equipment* sector are the main sources of embodied energy in China’s processing exports. Therefore, the similar role of China’s *Electrical and Machinery* sector also appears in its other embodied energy trade with developed areas such as European Union, as Tao et al. (2018) shows in their investigation on the energy embodied in China-EU manufacturing trade from 1995 to 2011.

**Table 1** Top 10 cross-border embodied energy flows between sectors (Unit: TJ)

| Source Country | Source Sector               | Target Country | Target Sector               | Flow Volume |
|----------------|-----------------------------|----------------|-----------------------------|-------------|
| Korea          | Electrical and Machinery    | China          | Electrical and Machinery    | 3.71E+08    |
| China          | Electrical and Machinery    | Korea          | Electrical and Machinery    | 2.30E+08    |
| Singapore      | Electrical and Machinery    | China          | Electrical and Machinery    | 2.05E+08    |
| Malaysia       | Electrical and Machinery    | Singapore      | Electrical and Machinery    | 1.67E+08    |
| China          | Electrical and Machinery    | Thailand       | Electrical and Machinery    | 1.46E+08    |
| Singapore      | Electrical and Machinery    | Malaysia       | Electrical and Machinery    | 1.25E+08    |
| China          | Electrical and Machinery    | Singapore      | Electrical and Machinery    | 1.18E+08    |
| Korea          | Metal Products              | China          | Metal Products              | 1.14E+08    |
| Malaysia       | Electrical and Machinery    | China          | Electrical and Machinery    | 1.12E+08    |
| Indonesia      | Electrical and Machinery    | Singapore      | Electrical and Machinery    | 9.88E+07    |

**Net embodied energy import and export**

Fig. 3 presents the structures of net embodied energy export for BRI countries. As shown in the left side of Figure 3, Russia, Indonesia, Uzbekistan, Kuwait, Serbia, Belarus, Oman, and Mongolia are large net importers of embodied energy in final use (EEY) and small net exporters of embodied energy in intermediate use (EEI), implying that these countries are the materials-suppliers and primary processors on the supply chain.
For Turkey, the Philippines, Israel, Bangladesh, and South Africa, their reliance on EEY is higher than on EEI, meaning that their final uses are mainly supplied by foreign countries. Vietnam, Slovakia, Slovenia, Romania, Thailand, Lithuania, Hungary, Estonia, and Azerbaijan import EEI for exporting EEY, suggesting that they play assembly roles or light industry producer roles in the production network. For China, the Czech Republic, and Poland, their energy reliance on EEI is higher than on EEY, implying that they import the embodied energy for the domestic final use and the re-exports.

As displayed on the right side of Fig. 3, Singapore, Malaysia, Ukraine, New Zealand, Lebanon, India supply more EEY than EEI, implying that their productions are close to the finished products of the supply chain. For the net exporters of embodied energy like South Korea, Saudi Arabia, and UAE, they are more balanced and have a more diversified production structure, which is different from Singapore and Malaysia, etc.

Econometric analysis of embodied energy trade between BRI countries

The estimation results of panel gravity model are reported in Table 2. Model (1) reports the ordinary least square (OLS) estimators with robust standard errors. Model (2) is the random effect (RE) model. Model (3) is the fixed effect model (FE) which accounts for individual heterogeneity, and Model (4) is the fixed effect model which accounts for both individual and year fixed effects. The results of model (4) are used as our reference to explain the embodied energy trade for two reasons. First, a fixed effect model is generally more appropriate than a random effects model for macroeconomic studies as it can allow the individual and/or time specific effects to be correlated with explanatory variables (Judson and Owen 1999). Second, the R-squared of model (4) is largest among four models, indicating that model (4) provides better goodness-of-fit compared with the other three models.

Rows 1 to 5 report the estimates of typical variables entering a basic gravity model of trade, including GDP per capita, population, and geographical distance. GDP per capita and population are statistically significant, which is consistent with previous related study (Fracasso 2014). GDP per capita and population are the pushers to bilateral embodied energy trade, and the positive impact of GDP per capita and population of the source country are larger than that of the target country. Geographical distance is the impeder to bilateral embodied energy trade. The result of geographical distance suggests that the transport cost is the main factor reducing the embodied energy trade between BRI countries. The elasticity of 0.878 implies that an increase of GDP per capita of an exporting country by 10% will increase the embodied energy exported to its partners by 8.78%, and this impact is statistically significant at the 1% level. These results show that adopting the gravity model of trade is appropriate to explain bilateral embodied energy trade.

Rows 6–13 present the estimates of the rest variables included in the gravity model of this paper. It is against the intuition at first thought that the industrial share of GDP is negatively related to the bilateral embodied energy trade. From the perspective of industry outsourcing and shift, however, the lower is the industrial share of GDP, the higher is its dependency on imported manufacturing products, which increases the embodied energy trade demand. Moreover, as exporters, countries with low industrial share are likely to increase the exports of services that is embodied energy-intensive (Liu et al. 2012; Sun et al. 2016) and increase bilateral embodied energy trade.

It is expected that higher energy intensity is positively associated with the increase of bilateral embodied energy trade. Higher energy intensity means more energy embodied in the goods or services, which results in more embodied energy exports or imports.

As expected, increasing intensity of involvement of a country in GVCs leads to more embodied energy flows with its trade partners. Countries join the GVCs through forward participation and backward participation, and many countries that have a high degree of forward participation also tend to have a high degree of backward participation (Li et al. 2019). This economic phenomenon indicates that countries with more embodied energy exports also tend to have more embodied imports. In either way, the embodied energy flows with trade partners will increase when a country has greater participation in GVCs.

GVC position index shows a negative impact on the embodied energy flow, which is different from the influence of GVC participation index. Due to larger GVC position index implies more upstreamness, therefore, countries in the upstream of GVCs tend to have few embodied energy flows. On the contrary, countries in the downstream of GVCs tend to have more embodied energy flows. This result is reflected in Figs. 1 and 2 as well.

Comparative analysis with previous related study

Duarte et al. (2018) studies the emissions embodied in international trade with similar gravity model; therefore, in this subsection we compare our main results with theirs. Both Duarte et al. (2018) and this study include distance, population, GDP per capita, and energy intensity in the gravity model. These two studies reveal that distance negatively
affects embodied energy/carbon trade, and that GDP per capita of importers, population, and energy intensity positively affect the bilateral embodied energy/carbon flow.

However, there are several differences between the findings of Duarte et al. (2018) and ours. First, we find that GDP per capita of exporters positively influences the bilateral embodied energy trade, but Duarte et al. (2018) find a negative impact GDP per capita of exporters on the bilateral embodied carbon trade. Our results do not support the pollution haven hypothesis for current BRI countries, which is totally different from Duarte et al. (2018) in this regard.

The reasons for these differences probably are related to the model setting and data coverage. Regarding the model setting, due to different research purposes, we consider structure factors such as industrial structure and GVC-related factors, which Duarte et al. (2018) does not consider. Nevertheless, Duarte et al. (2018) includes contiguity and institutional variables in the model such as Kyoto protocol, regional trade agreements between the trade partners (RTA), and accession of the trading pair to the World Trade Organization (BOTHIN) which we do not. Second, we carry out a panel data analysis with a time span of 14 years covering 64 BRI countries, and among them the majority is developing economies, but Duarte et al. (2018) does a panel analysis that uses data of a period of 1995–2009 covering 39 countries, and among them the majority is developed economies.

### Table 2 Estimation results of gravity model for embodied energy trade (2002–2015)

|      | (1)         | (2)         | (3)         | (4)         |
|------|-------------|-------------|-------------|-------------|
|      | OLS         | RE          | FE          | FE2         |
| GDPP_r | 0.646***    | 0.476***    | 0.866***    | 0.878***    |
|       | (68.50)     | (56.88)     | (88.00)     | (98.94)     |
| GDPP_s | 0.624***    | 0.190***    | 0.522***    | 0.535***    |
|       | (67.48)     | (22.75)     | (53.08)     | (60.24)     |
| POP_r  | 0.591***    | 0.497***    | 0.914***    | 0.925***    |
|       | (113.11)    | (58.55)     | (79.10)     | (91.84)     |
| POP_s  | 0.510***    | 0.237***    | 0.547***    | 0.558***    |
|       | (100.35)    | (27.89)     | (47.37)     | (55.42)     |
| GD_rs  | −0.648***   | −0.650***   | −90.198***  | −915.746    |
|       | (−74.57)    | (−22.23)    | (−74.27)    | (−0.49)     |
| IND_r  | 0.871***    | −0.261***   | −0.182***   | −0.312***   |
|       | (27.54)     | (−9.14)     | (−6.30)     | (−12.26)    |
| IND_s  | 0.889***    | 0.079***    | 0.050*      | −0.080***   |
|       | (27.76)     | (2.75)      | (1.74)      | (−3.13)     |
| El_r   | 0.380***    | 0.105***    | 0.080***    | 0.068***    |
|       | (27.63)     | (13.53)     | (10.66)     | (10.39)     |
| El_s   | 0.446***    | 0.166***    | 0.136***    | 0.124***    |
|       | (29.78)     | (21.37)     | (18.16)     | (19.02)     |
| GVC_PA_r | 0.194***   | 0.308***    | 0.345***    | 0.294***    |
|       | (5.72)      | (18.18)     | (20.77)     | (17.11)     |
| GVC_PA_s | 0.260***   | 0.921***    | 1.008***    | 0.958***    |
|       | (7.74)      | (54.41)     | (60.75)     | (55.73)     |
| GVC_PO_r | −2.469***  | −2.320***   | −2.616***   | −2.468***   |
|       | (−50.57)    | (−82.01)    | (−94.88)    | (−101.40)   |
| GVC_PO_s | −3.767***  | −2.142***   | −2.450***   | −2.302***   |
|       | (−76.52)    | (−75.72)    | (−88.85)    | (−94.58)    |
| Constants | −5.615***  | 17.864***   | 1418.784*** | 14000       |
|       | (−18.33)    | (34.29)     | (74.84)     | (0.49)      |
| Individual fixed effect | No          | No          | Yes         | Yes         |
| Year fixed effect | No          | No          | No          | Yes         |
| R-squared | 0.554      | 0.465       | 0.515       | 0.635       |
| Observations | 56448      | 56448       | 56448       | 56448       |

Significance at the 0.01, 0.05, and 0.10 levels are indicated by ***, **, *, respectively.
Uncertainties analysis and validation

One shortcoming of this paper, as pointed out by an anonymous reviewer, is the uncertainties caused by the energy uses by sectors in the Eora database. It should be noted that some energy data covered in the Eora are not updated frequently after 2008, especially after 2011, for example the energy data for Mainland of China are the same for 2011–2015. To see how big uncertainties could be, we have done a panel analysis using the data of 2002–2008. One uncertain result is that we cannot tell if the effects of GVC participation and the energy intensity of importing side are larger than the exporting side, which however does not lead to the de facto change of the other main results in the gravity analysis. The panel results are shown in Table 3.

Considering the updating frequency of energy data in Eora, we took energy intensity data from the World Development Indicators, rather than calculating them from the energy account and GDP information of Eora. To see the uncertainty caused by this dataset choice, we have done a panel analysis with the energy intensity calculated from Eora dataset. The results are shown in Table 4. As shown in this table, the effect of energy intensity that directly related to the dataset choice shows uncertainty to some extent. Nonetheless, most of the main results in the gravity analysis (compared with Table 2) still hold.

Concluding remarks and policy implications

In this paper, we analyze the embodied energy trade between BRI countries and explore the determinants of bilateral embodied energy trade through a panel gravity model. The main contribution of this study to the literature is that we analyze

Table 3 Estimation results of gravity model for embodied energy trade (2002–2008)

|                   | OLS       | RE        | FE        | FE2       |
|-------------------|-----------|-----------|-----------|-----------|
| GDPP_r            | 0.656***  | 0.651***  | 0.765***  | 0.854***  |
|                   | (50.51)   | (40.43)   | (31.22)   | (41.35)   |
| GDPP_s            | 0.633***  | 0.420***  | 0.293***  | 0.383***  |
|                   | (49.93)   | (26.05)   | (11.97)   | (18.52)   |
| POP_r             | 0.594***  | 0.661***  | 0.853***  | 0.946***  |
|                   | (81.03)   | (50.45)   | (28.98)   | (38.15)   |
| POP_s             | 0.511***  | 0.482***  | 0.351***  | 0.444***  |
|                   | (71.00)   | (36.81)   | (11.93)   | (17.90)   |
| GD_rs             | -0.652****| -0.631****| -16.826***| 3.2×10^3 |
|                   | (-53.25)  | (-22.44)  | (-3.72)   | (2.31)    |
| IND_r             | 0.936***  | -0.583*** | -0.849*** | -0.693*** |
|                   | (20.25)   | (-13.31)  | (-17.59)  | (-17.02)  |
| IND_s             | 0.967***  | -0.180*** | -0.494*** | -0.337*** |
|                   | (20.80)   | (-4.11)   | (-10.23)  | (-8.29)   |
| EI_r              | 0.299***  | 0.165***  | 0.146***  | 0.179***  |
|                   | (16.72)   | (11.67)   | (9.44)    | (13.76)   |
| EI_s              | 0.332***  | 0.203***  | 0.109***  | 0.142***  |
|                   | (16.77)   | (14.39)   | (7.05)    | (10.92)   |
| GVC_PA_r          | 0.325***  | 0.713***  | 0.734***  | 0.791***  |
|                   | (7.03)    | (29.37)   | (26.14)   | (33.12)   |
| GVC_PA_s          | 0.215***  | 0.064***  | 0.068***  | 0.125***  |
|                   | (4.64)    | (2.62)    | (2.43)    | (5.25)    |
| GVC_PO_r          | -4.016****| -2.387****| -2.231*** | -2.246*** |
|                   | (-55.42)  | (-45.55)  | (-39.76)  | (-47.34)  |
| GVC_PO_s          | -2.445****| -2.426****| -2.231*** | -2.246*** |
|                   | (-34.48)  | (-46.31)  | (-39.77)  | (-47.35)  |
| Constants          | -4.401****| 8.008***   | 266.682***| 5.0×10^4 |
|                   | (-10.59)  | (12.45)   | (3.76)    | (1.30)    |

Significance at the 0.01, 0.05, and 0.10 levels are indicated by ***, **, *, respectively.

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impacts of GVC participation index and GVC position index on the bilateral embodied energy trade, which has been rarely examined previously. In addition, we assess the embodied trade flows of BRI area that mostly covers developing countries from a systemic perspective, which supplement existing embodied energy research at supernational scale. The main conclusions and their policy implications are as follows. First, through embodied energy accounting, we find that 22% bilateral embodied trade concentrated in 10 embodied energy flow paths and 5% embodied energy flow paths account for 80% of the total bilateral embodied energy flow volume. China, South Korea, Singapore, and Russia play central roles in the BRI embodied energy trade. These results imply that BRI as a cooperation platform should strengthen the energy-saving cooperation between the major embodied energy trade partners and coordinate the planning of energy development among them. Besides, BRI should establish a monitor system to track the energy footprint change and the bilateral embodied energy trade change, and these main flow paths and major countries should be the focus targets of this system.

Second, the gravity analyses indicate that the positive effects on the bilateral embodied energy trade come from GDP per capita, population, energy intensity, and the extent of global value chain participation. The negative effects come from the industrial share of GDP, the global value chain position, and geographical distance. Most BRI countries are the middle income or below countries, their GDP per capita is likely to grow, and their participation in the GVCs will increase, which will increase the energy pressure of the BRI area. Under this scenario, energy intensity plays a crucial role in reducing the pressure of increasing energy footprint.

To reduce the energy footprint of BRI countries, the Belt and Road Energy cooperation platform should work closely to set up a series of programs that target energy efficiency as a top priority. These areas could be (a) the construction regional

Table 4: Estimation results using energy intensity from Eora (2002–2015)

|          | (1) OLS | (2) RE | (3) FE | (4) FE |
|----------|---------|--------|--------|--------|
| GDPP_r   | 0.603***| 0.462***| 0.798***| 0.829***|
|          | (62.48) | (57.29) | (84.05) | (98.20) |
| GDPP_s   | 0.605***| 0.126***| 0.415***| 0.464***|
|          | (63.25) | (15.73) | (43.81) | (54.76) |
| POP_r    | 0.594***| 0.549***| 0.909***| 0.900***|
|          | (112.80)| (58.74) | (74.82) | (87.38) |
| POP_s    | 0.510***| 0.263***| 0.546***| 0.568***|
|          | (94.86) | (28.12) | (44.66) | (54.73) |
| GD_rs    | -0.732****| -0.709****| -88.907***| -626.028 |
|          | (-76.66)| (-22.35) | (-66.23) | (-0.32) |
| IND_r    | 1.321***| -0.222***| -0.105***| -0.271***|
|          | (38.55) | (-6.45) | (-3.02) | (-9.10) |
| IND_s    | 1.288***| 0.072** | 0.065* | -0.038 |
|          | (38.77) | (2.11) | (1.86) | (-1.27) |
| EI_r     | 0.103***| -0.004** | -0.029***| -0.066***|
|          | (19.95) | (-1.99) | (-15.25) | (-38.92) |
| EI_s     | 0.052***| 0.065***| 0.032***| 0.001 |
|          | (9.04) | (34.17) | (17.23) | (0.64) |
| GVC_PA_r | 0.100***| 1.015***| 1.132***| 1.291***|
|          | (2.68) | (47.92) | (54.34) | (59.15) |
| GVC_PA_s | 0.099***| 0.329***| 0.299***| 0.372***|
|          | (2.64) | (15.56) | (14.44) | (17.41) |
| GVC_PO_r | -3.854***| -2.144***| -2.313***| -1.927***|
|          | (-72.62)| (-56.26) | (-62.22) | (-59.60) |
| GVC_PO_s | -2.337***| -2.192***| -2.477***| -2.186***|
|          | (-44.00)| (-58.37) | (-67.40) | (-68.51) |
| Constants| -1.134***| 19.965***| 1400.657***| 9906.481 |
|          | (-4.35) | (35.85) | (66.79) | (0.32) |
| Individual fixed effect | No | No | Yes | Yes |
| Year fixed effect | No | No | No | Yes |
| R-squared | 0.5558 | 0.3937 | 0.4474 | 0.6049 |
| Observations | 49560 | 49560 | 49560 | 49560 |

Significance at the 0.01, 0.05, and 0.10 levels are indicated by ***, **, *, respectively
smart power grid network that coordinates the supply and demand of electricity for the whole BRI area. (b) Setting up of the energy efficiency improvement fund that encourages the energy-saving practices and the technological transfer and support from developed areas to underdeveloped areas. (c) Harmonizing energy efficiency standards of major embodied energy import countries at the first step and gradually expanding to all BRI countries. (d) Establishment of a research institute network to undertake the energy efficiency policy dialogue, academic conferences and seminars, and professional training, etc.

In this study, no variables account for multilateral resistance, which implies that increasing competitiveness of the third economy C affects the bilateral trade between A and B (Anderson and van Wincoop 2003). This effect cannot be captured by monadic or dyadic variables in the gravity model. Several approaches have been proposed to deal with multilateral resistance. However, data features such as missing observations make it hard to choose the optimal method in all aspects and reach a conclusive result (Fracasso 2014). Further analysis should be devoted to deal with multilateral resistance in embodied energy trade between BRI countries.

Energy intensity plays a critical role in increasing the bilateral embodied energy trade. Further research on the determinants of the energy efficiency of BRI countries could be useful. Possible directions involve using panel quantile regression to analyze the impacts of resource endowment, energy price, government intervention, and general technology progress on total factor energy efficiency.

Embodied energy trade (Chen and Chen 2011; Sun 2018), virtual water trade (Zhai et al. 2019; Zhang et al. 2018), embodied land exchange (Chen and Han 2015), and embodied materials trade (Wiedmann et al. 2015) are hot topics in ecological footprints research. Designing a basic gravity model and extended gravity models including resource-specific variables to do a comparative study is also useful in revealing the common determinants of embodied resources exchange and the degree of resource-specific effects.

### Appendix

#### Table 5  List of BRI countries

| Region          | Country (code)                  | Region                      | Country (code)     |
|-----------------|---------------------------------|-----------------------------|--------------------|
| Asia-Oceania    | Brunei (BRN)                    | South Asia countries (8)    | Afghanistan (AFG)  |
| countries (14)  | Cambodia (KHM)                  |                              | Bangladesh (BGD)   |
|                 | China (CHN)                     |                              | Bhutan (BTN)       |
|                 | Indonesia (IDN)                 |                              | India (IND)        |
|                 | Laos (LAO)                      |                              | Maldives (MDV)     |
|                 | Malaysia (MYS)                  |                              | Nepal (NPL)        |
|                 | Mongolia (MNG)                  |                              | Pakistan (PAK)     |
|                 | Myanmar (MMR)                   |                              | Sri Lanka (LKA)    |
|                 | New Zealand (NZL)               | Central and Eastern European| Albania (ALB)      |
|                 | Philippines (PHL)               | countries (20)              | Belarus (BLR)      |
|                 | Singapore (SGP)                 |                              | Bosnia and Herzegovina (BIH) |
|                 | South Korea (KOR)               |                              | Bulgaria (BGR)     |
|                 | Thailand (THA)                  |                              | Croatia (HRV)      |
|                 | Vietnam (VNM)                   |                              | Czech Republic (CZE) |
|                 |                                 |                              | Estonia (EST)      |
| Central Asia    | Kazakhstan (KAZ)                |                              | Hungary (HUN)      |
| countries (5)   | Kyrgyzstan (KGZ)                |                              | Latvia (LVA)       |
|                 | Tajikistan (TJK)                |                              | Lithuania (LTU)    |
|                 | Turkmenistan (TKM)              |                              | Macedonia (MKD)    |
|                 | Uzbekistan (UZB)                |                              | Moldova (MDA)      |
|                 |                                 |                              | Montenegro (MNE)   |
| West Asia       | Azerbaijan (AZE)                |                              | Poland (POL)       |
| countries (17)  | Armenia (ARM)                   |                              | Serbia (SRB)       |
|                 | Bahrain (BHR)                   |                              | Slovakia (SVK)     |
|                 | Georgia (GEO)                   |                              | Slovenia (SVN)     |
|                 | Iran (IRN)                      |                              | Romania (ROU)      |
|                 | Iraq (IRQ)                      |                              | Russia (RUS)       |
|                 | Israel (ISR)                    |                              | Ukraine (UKR)      |
|                 | Jordan (JOR)                    | Africa and Latin America     | Egypt (EGY)        |
|                 | Kuwait (KWT)                    | countries (6)               | Ethiopia (ETH)     |
|                 | Lebanon (LBN)                   |                              | Madagascar (MDG)   |
|                 | Oman (OMN)                      |                              | Morocco (MAR)      |
|                 | Qatar (QAT)                     |                              | Panama (PAN)       |
|                 | Saudi Arabia (SAU)              |                              | South Africa (ZAF) |
|                 | Syria (SYR)                     |                              |                     |
|                 | Turkey (TUR)                    |                              |                     |
|                 | United Arab Emirates (UAE)      |                              |                     |
|                 | Yemen (YEM)                     |                              |                     |
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Data availability The authors declare that data supporting the findings of this study are available within the article.

Declarations

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