Factors Influencing Embodied Energy Trade between the Belt and Road Countries: A Gravity Approach

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

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Abstract

Energy is a basic factor input embodied in the production of goods and services. The rapid growth of trade between Belt and Road countries calls for the study of bilateral embodied energy trade between them. Using the Eora input-output database in 2015, this paper accounts the embodied energy trade between Belt and Road countries, followed by an investigation of the factors influencing the embodied energy trade through a gravity model, which is different from the conventional decomposition analysis. 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. 5% 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 GDP per capita and population are the key drivers of bilateral embodied energy trade, while the industrial share of GDP is negatively related to the trade. Energy intensity, especially that of importing countries, 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, trade

1. Introduction

Belt and Road Initiative (BRI) is an international development initiative that encompasses more than 60 economies, occupying 60% of the global population and 30% of the world's gross domestic product (GDP) (Zhang et al., 2019). Promoting multilateral trade is one of the main themes of BRI. Since the proposal of the BRI in 2013, the trade between China and other BRI countries has had a 13.4% growth rate year on year, reaching 1.44 trillion U.S. dollars and accounting for 39.9% of the global trade in 2017 (Center and SINOIMEX, 2018). Because of the sliced and geological-diversified production processes, international trade leads to the transfer of direct and indirect energy use. Rapid trade growth results in increasing huge amount of energy flow between BRI countries. Investigating the energy flow between BRI countries, thus, becomes critical for the energy-saving cooperation among BRI countries.

Direct energy flow is relatively easier to measure than indirect energy flow. To account for 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 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.

On the inter-provincial scale, 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 interprovincial 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 world input-output table with China's inter-provincial input-output table together. On the bilateral scale, 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, Zhu et al. (2020) analyzes the share of China's embodied energy in exports with major trading partners during the period of 2005-2015 and the forces driving the varied structure of shares. At the multilateral scale, Tian et al. (2017) accounts for the resources footprints embodied in the China-EU 27 countries trade. 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 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 (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. However, there are few studies about the embodied energy flow between BRI countries, where the trade mainly occurs between developing economies.

Additionally, previous studies on the drivers of embodied energy trade mainly use structural decomposition analysis (SDA) from the perspective of node. SDA decomposes changes in an aggregate indicator into several components with each associated with a predefined factor based on input-output models and has been widely used for energy and climate policy assessment and development (Wang et al., 2017). For example, Zhao et al. (2018) applies SDA to analyze the drivers of energy consumption embodied in the inter-provincial trade of China. Tao et al. (2018) investigates the driving forces of energy embodied in China-EU manufacturing trade from 1995 to 2011. Lan et al. (2016) explores factors influencing embodied energy change on a global scale. The SDA studies mentioned above decompose the total embodied energy change into several indicators, focusing on the node analysis and ignoring the investigations on the determinants of trade flow. On the one hand, the MRIO-based SDA studies can reveal in detail the impact of structure factor on the energy change (Feng et al., 2012; Su and Ang, 2012). On the other hand, SDA lacks a flexible modelization of qualitative factors and thus the flexibility of the analysis of the driving forces is limited (Wang et al., 2017). Consequently, the influence of other economic factors from the perspective of edge are ignored, such as the spatial character of trade flows and country/time-specific variables (Duarte et al., 2018). Given the limitation of SDA, Duarte et al. (2018) seeks to analyze the factors driving embodied carbon in international trade by combining MRIO and traditional gravity model.

In this study, we combine MRIO and gravity model to analyze factors driving the embodied energy in BRI trade and thus make two concrete contributions to the literature. First, we apply the MRIO model to measure the embodied energy flow between BRI countries and to uncover the main features of the flows, which enriches the embodied energy studies at the super-national scale and the embodied energy trade between developing economies. By identifying the key countries and main embodied energy flow, this paper is meaningful in providing suggestions for the energy-saving cooperation among BRI countries and thus contributing to the achievement of UN sustainable development goals. Second, we use a gravity model to explore the factors influencing the embodied energy trade between BRI countries, which supplements the SDA studies on the factors driving the embodied energy trade.

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

2. Materials and methods

2.1 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 (SRIO) 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 multi-lateral 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 for the global embodied energy flow using the full global Eora database and then extracting 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),

$$d_i^r + \sum_{s=1}^{m} \sum_{j=1}^{n} \omega_j^s \times z_{ji}^{sr} = \omega_i^r \times \left(\sum_{s=1}^{m} \sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} y_i^{rs} \right) \tag{1}$$

where d_i^r denotes the direct energy input of sector i of region r, z_{ji}^{sr} the intermediate use of goods by sector i of region r that is produced by sector j of region s, ω_j^s the embodied energy intensity of sector j of region s, and y_i^{rs} 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 matrix is expressed by Eq. (2),

$$D+WZ=WX \tag{2}$$

where $D=\begin{bmatrix} d_1^1 & d_2^1 & \cdots & d_n^m \end{bmatrix}$ is the vector of sectoral direct energy input, $Z=\begin{bmatrix} z_{11}^{11} & z_{12}^{11} & \cdots & z_{1n}^{1m} \\ z_{21}^{11} & z_{22}^{11} & \cdots & z_{2n}^{1m} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1}^{m1} & z_{n2}^{m1} & \cdots & z_{nn}^{mm} \end{bmatrix}$ is the intermediate matrix, $Y=\begin{bmatrix} y_1^{11} & y_1^{12} & \cdots & y_1^{1m} \\ y_2^{11} & y_2^{12} & \cdots & y_2^{1m} \\ \vdots & \vdots & \ddots & \vdots \\ y_n^{m1} & y_n^{m2} & \cdots & y_n^{mm} \end{bmatrix}$ is the final demand matrix, $W=\begin{bmatrix} \omega_1^1 & \omega_2^1 & \cdots & \omega_n^m \end{bmatrix}$ is the vector of sectoral embodied energy intensity, and $X=\begin{bmatrix} \sum_{s=1}^{m}\sum_{j=1}^{n} z_{1j}^{1s}+\sum_{s=1}^{m} y_1^{1s} & \cdots & 0 \\ 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sum_{s=1}^{m}\sum_{j=1}^{n} z_{nj}^{ms}+\sum_{s=1}^{m} y_n^{ms} \end{bmatrix}$ is the diagonal matrix of total output.

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

$$W=D(X\text{-}Z)^{-1} \tag{3}$$

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),

$$W=E(I\text{-}A)^{-1} \tag{4}$$

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

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

$$G=\widehat{W}Z=\begin{bmatrix} g_{11}^{11} & \cdots & g_{1n}^{1m} \\ g_{21}^{11} & \cdots & g_{2n}^{1m} \\ \vdots & \ddots & \vdots \\ g_{n1}^{m1} & \cdots & g_{nn}^{mm} \end{bmatrix} \tag{5}$$

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

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

$$H = \widehat{W}Y = \begin{bmatrix} h_1^{11} & \cdots & h_1^{1m} \\ \vdots & \ddots & \vdots \\ h_n^{m1} & \cdots & h_n^{mm} \end{bmatrix} \tag{6}$$

Based on Eq. (5) and Eq. (6), merging all sectors, i.e. $c^{rs} = \sum_{i=1}^{n} \sum_{j=1}^{n} g_{ij}^{rs} + \sum_{i=1}^{n} h_i^{rs}$, we obtain the embodied energy flow between countries, see Eq. (7),

$$C = \begin{bmatrix} c^{11} & \cdots & c^{1m} \\ c^{21} & \cdots & c^{2m} \\ \vdots & \ddots & \vdots \\ c^{m1} & \cdots & c^{mm} \end{bmatrix} \tag{7}$$

The energy embodied in region r's import of intermediate goods is expressed by Eq. (8),

$$TEIM^r = \sum_{i=1}^{n} \sum_{s=1(s\neq r)}^{m} \sum_{j=1}^{n} \omega_j^s z_{ji}^{sr} \tag{8}$$

The energy embodied in region r's export of intermediate goods is expressed by Eq. (9),

$$TEEX^r = \sum_{i=1}^{n} \sum_{s=1(s\neq r)}^{m} \sum_{j=1}^{n} \omega_i^r z_{ij}^{rs} \tag{9}$$

The net energy exports embodied in intermediate goods of region r is expressed by Eq. (10),

$$NEXZ^r = TEEX^r - TEIM^r \tag{10}$$

The energy embodied in region r's import of final goods is expressed by Eq. (11),

$$FEIM^r = \sum_{i=1}^{n} \sum_{s=1(s\neq r)}^{m} \omega_i^s y_i^{sr} \tag{11}$$

The energy embodied in region r's export of final goods is expressed by Eq. (12),

$$FEEX^r = \sum_{i=1}^{n} \sum_{s=1(s\neq r)}^{m} \omega_i^r y_i^{rs} \tag{12}$$

The net energy exports embodied in final goods of region r is expressed by Eq. (13),

$$NEXF^{r}=FEEX^{r}-FEIM^{r} \tag{13}$$

2.2 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 (Bergstrand, 1989), population (Fracasso, 2014), trade agreements (de Sousa, 2012), technology (Eaton and Kortum, 2002), geographical distance (Tinbergen, 1962), and institutional factors (Baltagi et al., 2003; de Groot et al., 2004) on trade have been quantified.

Following the previous research, we examine the impact of GDP per capita, population, and geographical distance on 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 energy consumption (Wang et al., 2014). Additionally, we study the impact of economic complexity on bilateral embodied energy trade. Economic complexity measures the diversification of productive structure based on the revealed comparative advantage (Hidalgo and Hausmann, 2009; Hidalgo et al., 2007). A country with higher economic complexity owns a more diversified productive structure and better quality of the exported products, which is measured by economic fitness (Tacchella et al., 2013; Tacchella et al., 2018).

Therefore, economic complexity could have a potential impact on the bilateral embodied energy trade. Considering all the factors aforementioned, we construct an extended gravity model as Eq. (14) to examine their impacts on the bilateral embodied energy flow between BRI countries.

$$ln(c^{rs})=K+\alpha lnGDPP_r+\beta lnGDPP_s+\gamma lnPOP_r+\delta lnPOP_s+\lambda lnGD_{rs}+\phi lnEF_r$$
$$+\zeta lnEF_s+\xi lnIND_r+\vartheta lnIND_s+\eta lnEI_r+\theta lnEI_s+\varepsilon_{rs} \quad (14)$$

where c^{rs} denotes the bilateral embodied energy flow between country r and s; K is the constant variable; $GDPP_r$ is the GDP per capita of country r; POP_r is the population of r; EF_r is the economic fitness of r; EI_r is the direct energy intensity of country r; GD_{rs} is the geographical distance between r and s, measured by the range between the capital city of trading partners; IND_r is the industrial share of GDP of r; and ε_{rs} is the residual term. α and β can be expressed as the income elasticities of trade; γ and δ are the population elasticities of trade; λ is the distance elasticity; ϕ and ζ are the economic-fitness elasticities; ξ and ϑ are the industrial structure elasticities, and η and θ are the energy intensity elasticities.

2.3 Data source

There are several worldwide input-output databases for MRIO 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 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 and energy use by sector 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 B1 are included in this study. 2015 global input-output table in Eora is used in this study.

GDP per capita, population, energy intensity (mega Joule per GDP), and industry share (including construction) of GDP data are from the World Development Indicators of World Bank, and GDP is measured at purchasing power parity and converted to 2011 US dollar level; economic fitness data are from World Bank (Tacchella et al., 2018), and a brief introduction of the method to calculate economic fitness is presented in Appendix A; and geographic distance (kilometers) is available at CEPII (Mayer and Zignago, 2012). Fossil energy trade data are from the UN Comtrade database. All these data are in 2015.

3. Results

3.1 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 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-orders feature of energy transfer among economies. Comparing the direct fossil energy trade feature and the embodied energy trade feature, therefore, reveals more information for policymakers.

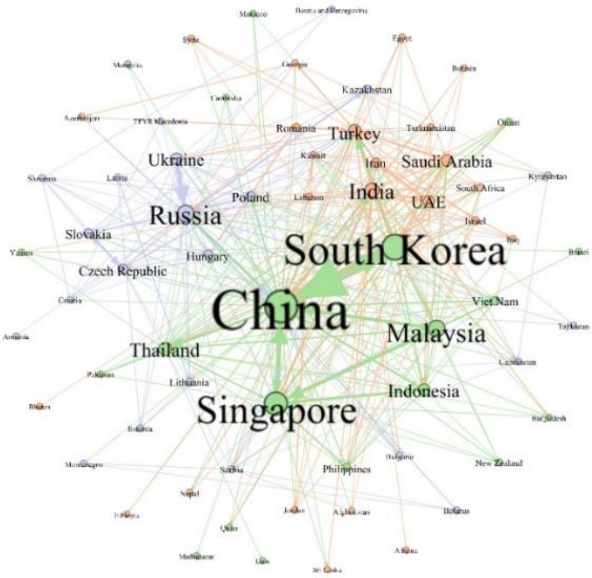

Figure 1 Visualization of BRI embodied energy trade

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.

Major and active countries in the BRI embodied energy trade is presented in Figure 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 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 the Philippines are the top 5 net importers among BRI countries.

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. (2020). 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 net exporter in the global embodied energy calculation, and it is shown by Han et al. (2020) 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 increases as time goes by. Han et al. (2020) uses 65 countries as BRI countries for their analysis, while we use 70 countries. Therefore, there is opposite result due to the different geographic coverages.

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 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 successful, and the reason behind this is its net export. In terms of embodied energy terms, Singapore is shown as an embodied energy net exporter. Figure 3 in section 3.2 also shows that Singapore net exports more embodied energy in final uses than the embodied energy in 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), 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 Figure 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.

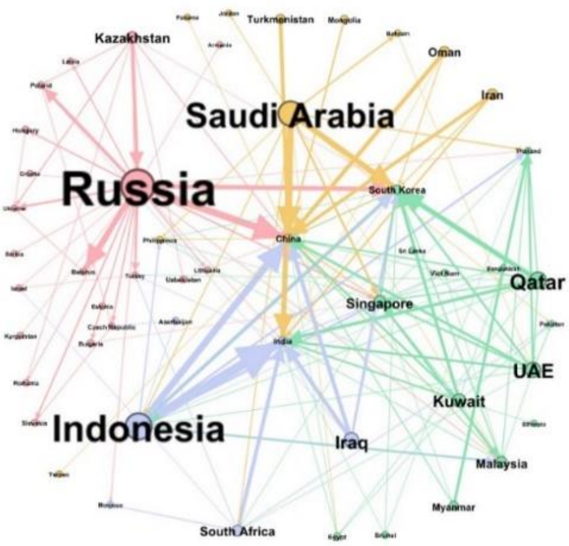

Figure 2 Visualization of BRI fossil energy trade

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 (2.45E+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 determine the flow directions of embodied energy trade.

The comparison between the embodied energy trade and the fossil energy trade also highlights that China is a major net importer both of fossil energy and of 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.

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

Source		**Target**		**Flow Volume**
Country	**Sector**	**Country**	**Sector**	
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

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.

3.2 Net embodied energy import and export

Figure 3 presents roughly the national positions in the BRI production network. 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 use is 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 re-exports.

As displayed on the right side of Figure 3, Singapore, Malaysia, Ukraine, New Zealand, Lebanon, India supply more EEY than EEI, implying that their production positions 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*.

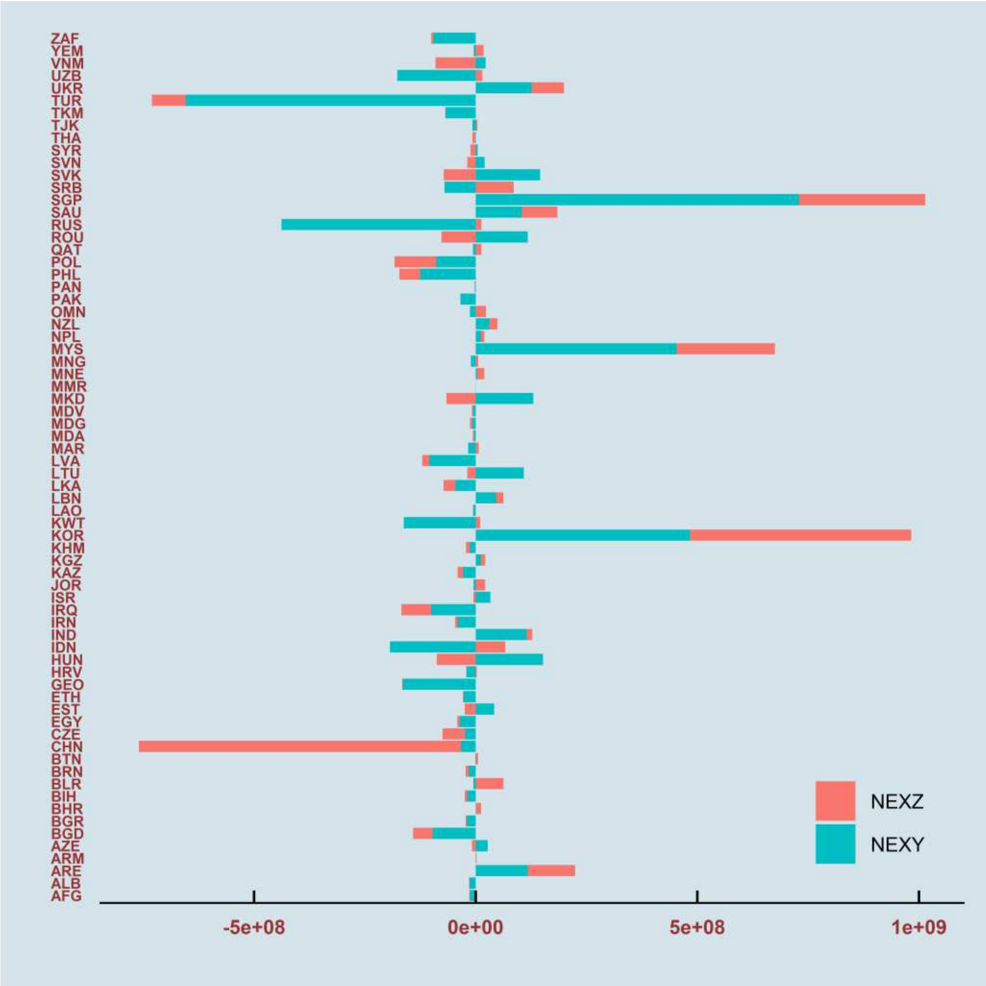

Figure 3 Structure of net embodied energy export

Note: NEXZ is an abbreviation of net embodied energy export in intermediate use, and NEXY is the abbreviation of net embodied energy export in final use. Country codes use ISO 3166-1 alpha-3 standard (https://www.iso.org/obp/ui/#search/code/) and are listed in Appendix B. Unit is TJ for x-axis.

3.3 Econometric analysis of embodied energy trade between BRI countries

The ordinary least squares (OLS) cross-sectional estimates are reported in Table 2.

Column (1) reports the estimates of typical variables entering a basic gravity model of trade, including GDP per capita, population, and geographical distance. All variables 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 and can significantly offset the push impact of the population. 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 0.810 implies that an increase of GDP per capita of an exporting country by 10% will increase the embodied energy exported to its partners by 8.1%, 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.

Column (2) presents the estimates of the full gravity model of this paper. Adding economic fitness, energy intensity, and industrial share as independent variables increases the goodness of fit of the gravity model. Comparing with the basic gravity model, the positive effect of GDP per capita and that of population size on bilateral embodied energy trade increase significantly, while the effect of geographic distance remains stable.

Economic fitness is positively related to the volume of embodied energy trade. The reason behind this result is that “the larger is the fitness of a country, the more diversified is its export and the larger is the quality of the exported product”, as

Tacchella et al. (2012) argued. On the one hand, the diversification of export products increases the number of trade partners and thus the embodied energy trade. On the other hand, the better quality of the exported product implies relatively high energy efficiency, which decreases the trade demand. The relatively low effect of economic fitness may be the result of the hedge effect between them.

Table 2 Gravity regression: OLS cross-sectional estimates

	C^{rs}	
Variables	(1)	(2)
GD_rs	-0.528^{***} (0.029)	-0.521^{***} (0.028)
GDPP_r	0.810^{***} (0.027)	0.991^{***} (0.031)
GDPP_s	0.737^{***} (0.027)	0.910^{***} (0.031)
POP_r	0.539^{***} (0.016)	0.592^{***} (0.016)
POP_s	0.505^{***} (0.016)	0.558^{***} (0.016)
IND_r		-0.887^{***} (0.086)
IND_s		-0.809^{***} (0.086)
EF_r		0.025^{***} (0.005)
EF_s		0.025^{***} (0.005)
EI_r		0.297^{***} (0.056)
EI_s		0.532^{***} (0.056)
Constant	-0.298 (0.456)	0.429 (0.490)
Observations	4830	4830
R^2	0.390	0.440
Adjusted R^2	0.389	0.438
Residual Std. Error	1.731(df=4824)	1.660(df=4818)
F Statistic	615.996^{***}(df=5;4824)	343.743^{***}(df=11;4818)

Note: * represents p<0.1, ** p<0.05, and *** p<0.01.

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 importing 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. It is worthy of attention that the push effect of the energy intensity of the importer is larger than that of the exporter.

3.4 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) finds 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. Additionally, we report that the positive impact of energy intensity of importers is larger than that of exporters, while Duarte et al. (2018) takes the contrary side.

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 economic complexity, 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 cross-sectional analysis that only uses data of 2015 covering 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.

3.5 Robustness check

Rounding errors in official statistics and limitation of data collection in building an input-output database result in missing bilateral embodied energy flows or zero-flows. Consequently, the sample selection problem and biased estimation appear in the presence of high-order moments of the errors. To address these problems, Poisson Pseudo-Maximum Likelihood (PPML) estimator is proposed (Silva and Tenreyro, 2006). PPML estimates are reported in Table 3. Comparing Table 2 and Table 3, we find that PPML estimates are consistent with OLS results. Therefore, our results are robust to changes in the estimation methods.

Table 3 Gravity regression: PPML cross-sectional estimates

	C^{rs}	
Variables	(1)	(2)
GD_rs	-0.041*** (0.002)	-0.041*** (0.002)
GDPP_r	0.064*** (0.002)	0.079*** (0.002)
GDPP_s	0.058*** (0.001)	0.072*** (0.001)
POP_r	0.042*** (0.001)	0.046*** (0.001)
POP_s	0.040*** (0.001)	0.043*** (0.001)
IND_r		-0.072*** (0.007)
IND_s		-0.065*** (0.007)
EF_r		0.002*** (0.000)
EF_s		0.002*** (0.000)
EI_r		0.023*** (0.004)
EI_s		0.042*** (0.004)
Constant	1.507 (0.035)	1.571 (0.038)

Note: * represents $p<0.1$, ** $p<0.05$, and *** $p<0.01$.

4. Discussion

In this study, there are no variables to 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 an identical result (Fracasso, 2014). Further analysis is called to deal with multilateral resistance in embodied energy trade between BRI countries.

BRI countries develop rapidly and increasing economies join this initiative. Once the annual global input-output tables are updated, embodied energy accounting can be updated accordingly, and a panel data model could be established to better estimate the factors influencing bilateral embodied energy flow between BRI countries. Furthermore, comparison studies between the embodied energy flow between OECD and that between BRI countries are important in promoting the green development of BRI, which is also useful to reveal more information about the different impacts caused by North-North trade (Lin and Xu, 2019; Sun et al., 2018; Wang and Zhou, 2019).

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), 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 useful in revealing the common determinants of embodied resources exchange and the degree of resource-specific effects.

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 direct could be using panel quantile regression to analyze the impacts of resource endowment, energy price, government intervention, and general technology progress on total factor energy efficiency.

5. Conclusion and policy implications

This study accounts for the embodied energy trade between BRI countries using the Eora input-output database and explores the determinants of bilateral embodied energy trade through a gravity model, which are the main contributions of this study to the literature. 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 bilateral embodied energy trade change, and these main flow paths and major countries should be the focus targets of this system.

Second, through comparing the net embodied energy export in intermediate goods and that in final use, we reveal roughly countries' positions in the BRI production network, and find that Russia and Indonesia are the materials-suppliers and primary processors on the supply chain, Vietnam and Slovakia are assemblers or light industry producers, China and the Czech Republic import the embodied energy for the domestic final use and re-exports, Singapore and Malaysia are the suppliers of the finished product, and South Korea is the balanced supplier of semi-finished products and finished products. These results suggest that green financial policy and green development fund support should consider the national positions along the supply chain to improve the green supply chain management performance.

Third, GDP per capita and population are the main pushers to the bilateral embodied energy trade, and the industrial share of GDP is negatively related to the embodied energy trade. Most BRI countries are the middle income or below countries, and their GDP per capita is likely to grow, which will increase the energy pressure of the BRI area. Under this scenario, energy intensity, especially that of importing countries, 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 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 expand 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*.

Fourth, geographical distance reduces the embodied energy flow. With the development of infrastructure connecting BRI countries, however, it is expected in the future its effect would decrease. The rapid development of infrastructure highlights the importance of energy efficiency improvements of main embodied energy trade economies for the sustainable development of BRI.

Last, China, Japan, South Korea, Australia, New Zealand and 10 countries (Members of Association of Southeast Asian Nations, ASEAN) reached the Regional Comprehensive Economic Partnership (RCEP) agreement in November 2020. Except for Japan and Australia, the other 13 members in RCEP are examined in this study. There exist strong economic complementarities among the countries of BRI and RCEP and increasing intermediate goods trade will lead to more embodied energy trade after the implementation of RCEP. Consequently, BRI and RCEP should be coordinated closely. As we discussed in the third concluding remark, energy efficiency should be a top priority of BRI cooperation, and many country leaders, such as President Xi Jinping of China, call on the green recovery from COVID-19 crisis. Therefore, we suggest that the governments of RCEP and BRI countries should strengthen the energy efficiency and green development cooperation, such as purchasing higher energy efficiency products and services and renewable energy in the government procurements and encouraging the green technologies transfer from developed economies to the developing economies.

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Appendixes

Appendix A: Method of calculating economic fitness

The main argument behind the mathematical approach to calculate the economic fitness is as follows: on the one hand, countries that export only a few products tend to export the products which are generally exported by almost all countries, and these products should have a low degree of complexity. On the other hand, countries that can export almost all products are the ones able to export the most exclusive products. As Tacchella et al. (2013) argued, "*While it appears reasonable to measure the competitiveness/fitness of a country through the sum of the complexity of the products of the export basket, the complexity of a product cannot be defined in terms of the average of the fitnesses of the exporters. The definition of the complexity of the product must account for the information that if a poorly diversified country is able to export a given product, very likely this product requires a low level of sophistication.*" In mathematical terms, this calls for an iterative method that is composed of two steps at each iteration. First, the intermediate variables $\widetilde{EF_r^{(o)}}$ and $\widetilde{Q_p^{(o)}}$ are expressed as follows:

$$\widetilde{EF_r^{(o)}} = \sum_p M_{rp} \, Q_p^{(o-1)} \tag{A.1}$$

and

$$\widetilde{Q_p^{(o)}} = \frac{1}{\sum_p M_{rp}\left(1/EF_r^{(o-1)}\right)} \tag{A.2}$$

Then the countries' fitness and the products' complexity at the order o are defined as Eq. (A.3) and Eq. (A.4)

$$EF_r^{(o)} = \frac{\widetilde{EF_r^{(o)}}}{<\widetilde{EF_r^{(o)}}>_r} \qquad (A.3)$$

and

$$Q_p^{(o)} = \frac{\widetilde{Q_p^{(o)}}}{<\widetilde{Q_p^{(o)}}>_r} \qquad (A.4)$$

The initial conditions are $Q_p^0=1 \, \forall p$, and $EF_r^0=1 \, \forall r$. The variable EF is termed as economic fitness that measures the level of competitiveness while Q is the complexity of products. The elements M_{rp} are the elements of the binary country-product matrix P, where the element $M_{rp}=1$ if country r exports product p, 0 otherwise.

Appendix B:

Table B1 List of BRI countries

Region	Country (code)	Region	Country (code)
Asia-Oceania countries (14)	Brunei (BRN)	South Asia countries (8)	Afghanistan (AFG)
	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 countries (20)	Albania (ALB)
	Philippines (PHL)		Belarus (BLR)
	Singapore (SGP)		Bosnia and Herzegovina (BIH)
	South Korea (KOR)		Bulgaria (BGR)
	Thailand (THA)		Croatia (HRV)
	Vietnam (VNM)		Czech Republic (CZE)
Central Asia countries (5)	Kazakhstan (KAZ)		Estonia (EST)
	Kyrgyzstan (KGZ)		Hungary (HUN)
	Tajikistan (TJK)		Latvia (LVA)
	Turkmenistan (TKM)		Lithuania (LTU)
	Uzbekistan (UZB)		Macedonia (MKD)
West Asia countries (17)	Azerbaijan (AZE)		Moldova (MDA)
	Armenia (ARM)		Montenegro (MNE)
	Bahrain (BHR)		Poland (POL)
	Georgia (GEO)		Serbia (SRB)
	Iran (IRN)		Slovakia (SVK)
	Iraq (IRQ)		Slovenia (SVN)
	Israel (ISR)		Romania (ROU)
	Jordan (JOR)		Russia (RUS)
	Kuwait (KWT)		Ukraine (UKR)
	Lebanon (LBN)	Africa and Latin America countries (6)	Egypt (EGY)
	Oman (OMN)		Ethiopia (ETH)
	Qatar (QAT)		Madagascar (MDG)
	Saudi Arabia (SAU)		Morocco (MAR)
	Syria (SYR)		Panama (PAN)
	Turkey (TUR)		South Africa (ZAF)
	United Arab Emirates (UAE)		
	Yemen (YEM)		

Availability of data and materials

The authors declare that data supporting the findings of this study are available within the article.

Author's contributions

Dr. Xiaoqi Sun is responsible for conceptualization, methodology, formal analysis, software, and Dr. Qing Shi is responsible for writing original draft, and visualization.

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Ethics declarations

Ethics approval and consent to participate.

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare no competing interests.

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Figures

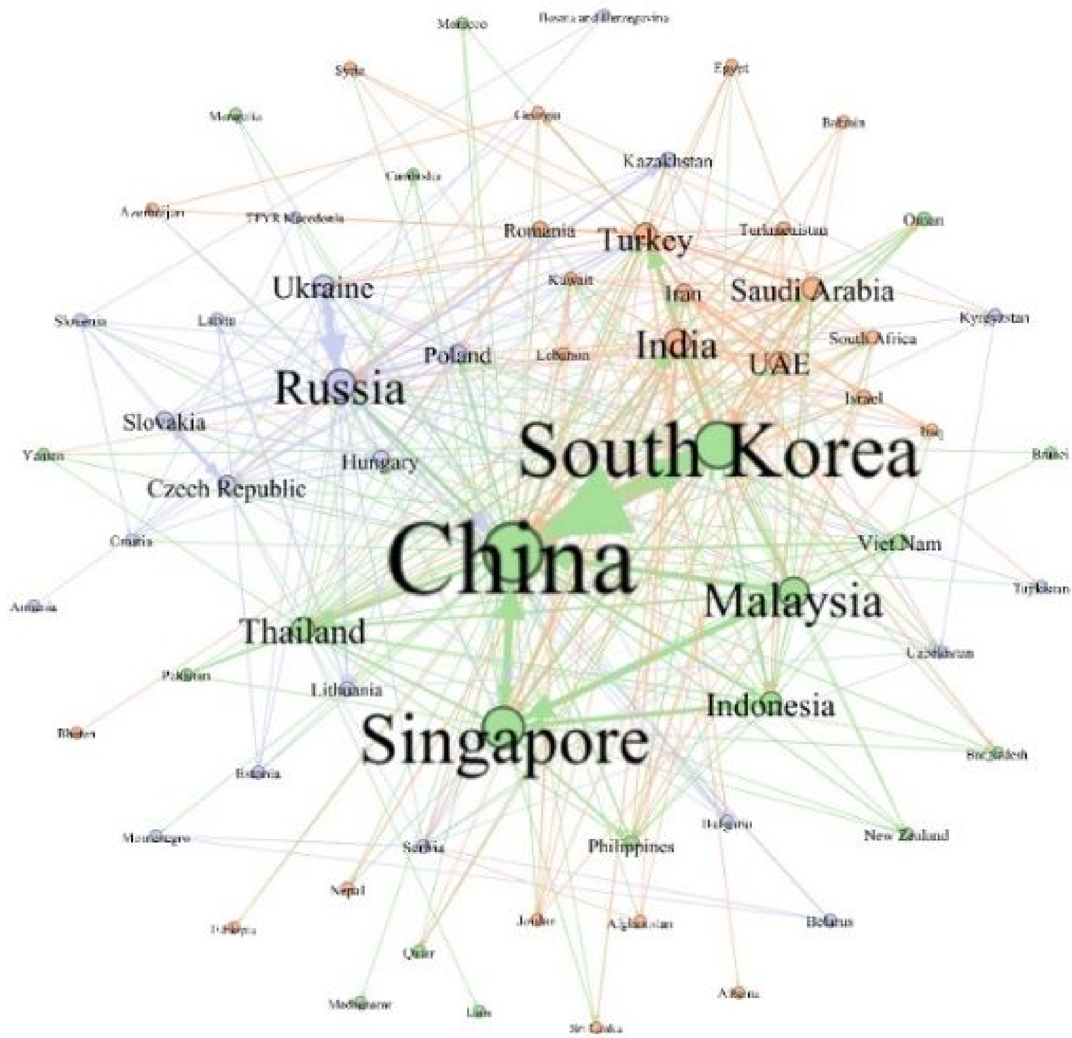

Figure 1

Visualization of BRI embodied energy trade

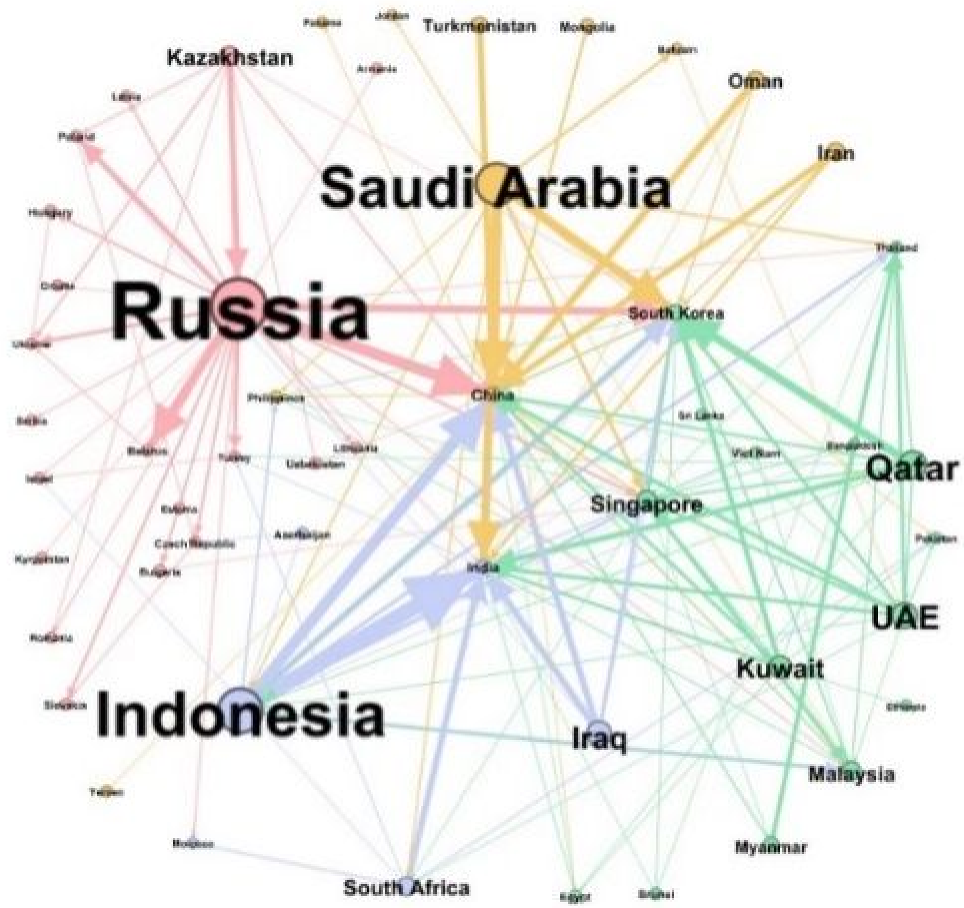

Figure 2

Visualization of BRI fossil energy trade

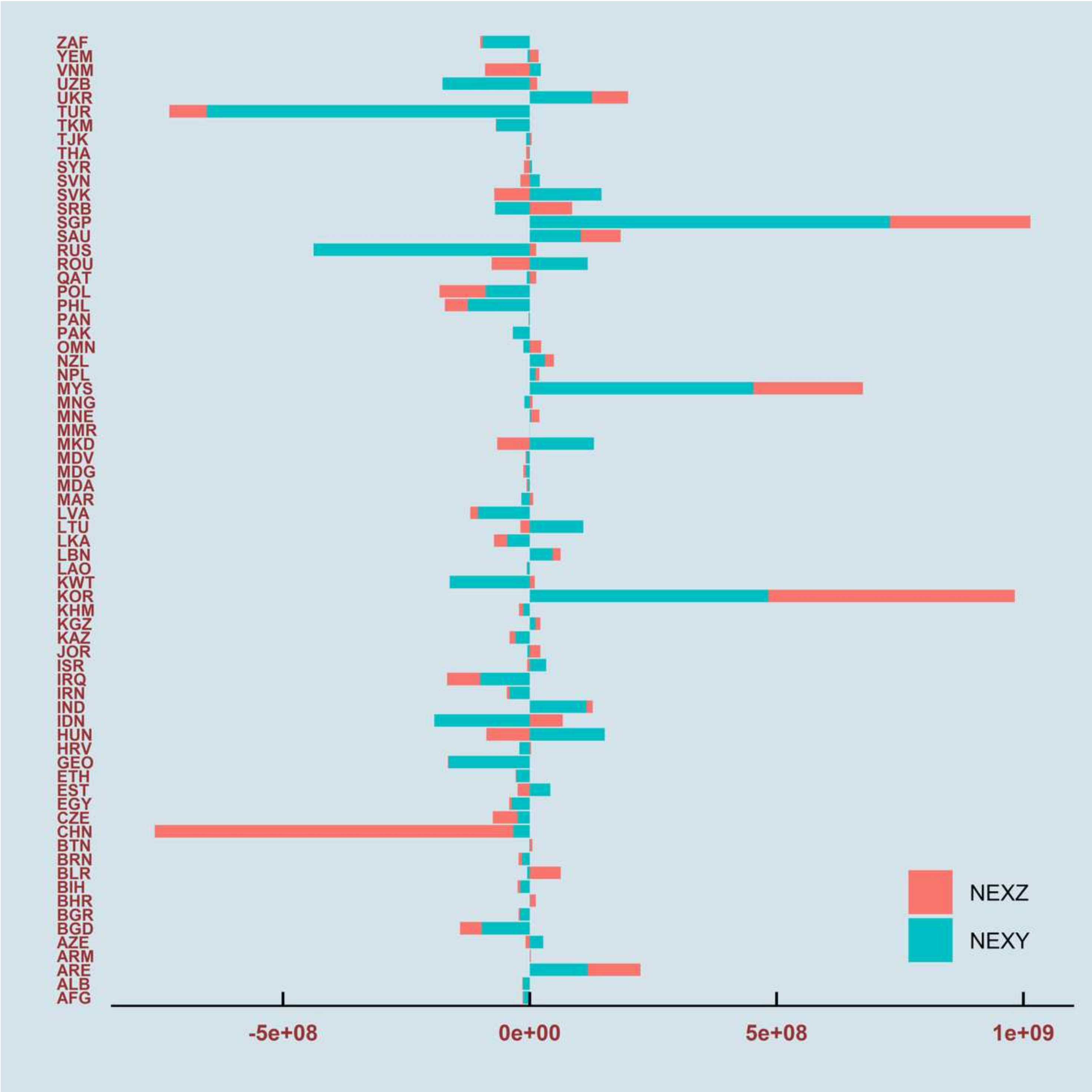

Figure 3

Structure of net embodied energy export