Embodied Carbon Flows among Belt and Road Countries: An Environmentally Extended Multi-Regional Input–Output Analysis

Sicheng Zhao

School of Economics and Management, Southeast University, Nanjing, China
1306965479@qq.com

Abstract. The expansion of trade and production networks under the Belt and Road Initiative (BRI) has strengthened economic cooperation while redistributing carbon emissions across national borders. This study quantifies embodied carbon flows among 60 BRI countries using environmentally extended multi-regional input–output models for 2015 and 2023. The analysis draws on the EMERGING V2 database (245 economies, 133 sectors) and its corresponding sector-level CO_2 emissions inventory. Consumption-based emissions (CBE), production-based emissions (PBE), and national net embodied carbon balances are calculated to identify the distribution of carbon responsibilities within BRI supply chains. The results show that intra-BRI embodied carbon was highly concentrated in a few large economies. The results reveal that intra-BRI embodied carbon was highly concentrated. China recorded the highest CBE and PBE in both years, followed by India and Russia, with the emission levels of several major economies increasing markedly by 2023. Most countries were net embodied carbon importers, although their share remained broadly stable, declining from 78.3% in 2015 to 76.7% in 2023. China remained a central node in the regional carbon network: India and Russia were among its most important embodied carbon partners, while India was its largest export destination. Moreover, the declining domestic-demand share of China's PBE indicates the growing influence of final demand from other BRI countries. These findings provide evidence for differentiated mitigation responsibilities and stronger low-carbon cooperation along BRI supply chains.

Keywords: Belt and Road Initiative; embodied carbon flows; environmentally extended multi-regional input–output model; consumption-based emissions; production-based emissions

1 Introduction

The Belt and Road Initiative (BRI) has strengthened economic connectivity across Asia, Europe, Africa, and the Middle East through trade, investment, and infrastructure development. These expanding economic linkages can support industrialization and regional development, but they may also increase energy demand and redistribute environmental pressures through cross-border supply chains. In particular, the production

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of traded goods and services generates carbon emissions in producing countries while satisfying consumption and investment demand elsewhere. Consequently, territorial emission inventories alone cannot fully reveal the allocation of carbon emissions and mitigation responsibilities within the BRI economic system. Previous research has also emphasized that the BRI's environmental consequences require systematic assessment alongside its economic benefits [1][2].

International trade creates a spatial separation between the consumption of products and the emissions generated during their production. Under production-based accounting, emissions are attributed to the economies in which they physically occur. Consumption-based accounting, by contrast, reallocates supply-chain emissions to the economies whose final demand ultimately drives production. Early studies demonstrated that a substantial amount of CO_2 is embodied in international trade and that the choice of accounting principle can considerably affect the allocation of national emission responsibilities [3][4]. Emission transfers through international trade also increased significantly during the expansion of global production networks, partially offsetting territorial emission reductions in some importing economies [5]. These findings highlight the need to consider both production- and consumption-based perspectives when evaluating regional carbon responsibilities.

Environmentally extended multi-regional input–output (EE-MRIO) analysis provides an appropriate framework for this purpose. By integrating intersectoral transactions, interregional trade, final demand, and sector-level emission data, EE-MRIO models can trace both direct and indirect emissions throughout complex supply chains. Unlike analyses based only on bilateral trade statistics, this approach captures emissions generated by upstream production stages and assigns them to the final consumers responsible for the associated demand [6]. The development of global MRIO databases with detailed geographical and sectoral coverage has further improved the ability to quantify environmental pressures embodied in international trade [7].

Although the literature on global embodied emissions is extensive, several issues remain relevant to the BRI context. First, BRI countries differ substantially in economic size, industrial structure, energy composition, and positions within regional value chains. Major manufacturing and resource-producing economies may bear considerable production-related emissions, whereas economies relying more heavily on imported products may shift part of their consumption-related carbon burden to trading partners. Second, the growth of trade among developing and emerging economies has altered the geography of global emissions. The expansion of South–South trade has increased the importance of developing countries as both producers and consumers in carbon-intensive supply chains [8]. Third, many global databases provide less detailed or less reliable information for small and medium-sized emerging economies, limiting the accurate representation of their roles in regional carbon flows. These issues make a BRI-focused assessment using a database with broad country coverage and detailed sectoral information particularly valuable.

This study therefore examines embodied carbon flows among 60 BRI countries in 2015 and 2023 using an EE-MRIO model. The analysis is based on the EMERGING V2 database [9] and its accompanying CO_2 emissions inventory, covering 245 economies and 133 sectors. The original economic system is aggregated into 60 individual

BRI countries and one Rest of the World region. The study calculates CBE, PBE, and national net embodied carbon balances within the BRI system. China's major embodied carbon import sources and export destinations are examined separately because of its central position in BRI production and trade networks.

This study makes three main contributions. First, it provides a comparative assessment of embodied carbon flows in 2015 and 2023, revealing changes in the distribution of consumption- and production-related emissions among BRI countries. Second, it identifies the relative positions of countries as net importers or exporters of embodied carbon, thereby illustrating the separation between consumption benefits and production-side environmental burdens. Third, it evaluates China's bilateral embodied carbon linkages with other BRI economies. The findings can provide empirical support for differentiated mitigation responsibilities, cleaner production cooperation, and coordinated supply-chain decarbonization across BRI countries.

2 Research Methods

2.1 Data Sources and Research Scope

This study employs the Multi-regional Input–Output Table for the Global Emerging Economies (EMERGING) V2 and its accompanying CO_2 emissions inventory. The database [9] covers 245 economies and 133 production sectors, providing detailed information on intermediate inputs, final demand, gross output, and interregional economic linkages. Compared with EMERGING 1.0, EMERGING V2 removes the original 27th sector and improves the calibration of the intermediate transaction matrix, import and export volumes, and gross output, particularly for the electricity, transportation, and energy sectors. The database also places particular emphasis on improving the representation of small- and medium-sized emerging economies.

Data for 2015 and 2023 are selected to conduct a comparative analysis. The main economic variables include the intermediate transaction matrix Z, final demand matrix F, and gross output vector X. The database also provides the ISO3 codes of the 245 economies and detailed classifications of the 133 sectors. Using a consistent database and sectoral classification for both years facilitates the comparison of production linkages, final-demand drivers, and embodied carbon flows among Belt and Road Initiative (BRI) countries. The comparison is intended to identify structural changes between 2015 and 2023 rather than establish the causal effects of any specific policy. Following the database's compilation convention, all monetary values in the EMERGING V2 tables are expressed in current prices, and no constant-price adjustment was applied in this study; the comparison between 2015 and 2023 therefore partly reflects price and exchange-rate movements in addition to real changes in production and demand.

Sector-level emissions are obtained from the EMERGING CO_2 Inventory, which integrates emissions data from the International Energy Agency (IEA) database and the China Emission Accounts and Datasets (CEADs). It reports CO_2 emissions from fossil fuel combustion and energy consumption at the economy–sector level in million tonnes of CO_2 equivalent (Mt CO_2eq). The inventory distinguishes seven energy categories: (1) coal, (2) natural gas, (3) oil products, (4) crude oil, natural gas liquids, and refinery

feedstocks, (5) other energy sources, (6) oil shale and oil sands, and (7) peat and peat products. In this study, emissions from the seven energy categories are summed to obtain the direct CO_2 emissions of each economy–sector unit. These emissions are subsequently matched with sectoral gross output to calculate direct carbon emission intensities.

Regarding the geographical scope, 60 BRI countries are treated as individual regions, while the remaining 185 economies are aggregated into a single Rest of the World (ROW) region. The original classification of 133 sectors is retained. Consequently, the original 245-economy MRIO system is transformed into a system comprising 60 BRI countries and one ROW region, with a total of 8113 region–sector units. The intermediate transaction matrix, final demand matrix, gross output vector, and sectoral emissions inventory are aggregated using the same regional classification for both 2015 and 2023 to ensure temporal comparability. For final demand, the three categories reported for each economy are first summed and then aggregated into the corresponding 61 destination regions.

By integrating the MRIO tables with the sector-level CO_2 emissions inventory, this study constructs environmentally extended MRIO systems for 2015 and 2023. These systems are used to quantify the CO_2 emissions generated along domestic and international supply chains to satisfy the final demand of BRI countries and to examine changes in the magnitude, direction, and spatial distribution of embodied carbon flows between the two years.

2.2 Regional and Sectoral Aggregation

To focus on embodied carbon flows among BRI countries, the 245 economies in the original EMERGING V2 database were aggregated into 61 regions. Sixty BRI countries were retained as individual regions, while the remaining 185 economies were combined into a single ROW region. The original classification of 133 sectors was retained, resulting in 8,113 region–sector units

The intermediate transaction matrix, gross output, final demand, and sectoral CO_2 emissions were aggregated according to this regional classification. Specifically, the intermediate inputs and gross outputs of economies assigned to ROW were summed by sector, while the corresponding data for each BRI country were retained separately. Sectoral CO_2 emissions from the seven energy categories were also summed to obtain the total direct emissions of each region–sector unit.

The original database reports three final-demand categories for each economy, household final consumption expenditure, government final consumption expenditure, and gross capital formation, which were first summed to obtain each economy's total final demand and then aggregated into the 61 destination regions. The resulting final demand matrix therefore represents the demand of each BRI country and ROW for products supplied by all region–sector units.

The same aggregation procedure was applied to the 2015 and 2023 datasets to ensure consistency and comparability between the two years. The final dataset thus consists of a 61-region and 133-sector environmentally extended input–output system, which

provides the basis for measuring embodied carbon flows among BRI countries while accounting for their economic linkages with the rest of the world.

2.3 Environmentally Extended Multi-Regional Input–Output Model

An environmentally extended multi-regional input–output (EE-MRIO) model was used to estimate the CO_2 emissions embodied in the final demand of BRI countries. All variables refer to the aggregated input–output system comprising 60 BRI countries and the ROW, with 133 sectors in each region.

The direct input coefficient matrix and the Leontief inverse are calculated as:

$$\mathbf{A} = \mathbf{Z}\,\widehat{\mathbf{X}}^{-1},\ \ \mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{1}$$

where $\mathbf{Z}$ is the intermediate transaction matrix, $\widehat{\mathbf{X}}$ is the diagonal matrix of gross output, and $\mathbf{I}$ is the identity matrix. The direct input coefficient matrix $\mathbf{A}$ represents the direct production inputs required among region–sector units, while the Leontief inverse $\mathbf{L}$ captures both direct and indirect production requirements throughout the supply chain.

The direct CO_2 emission intensity of each region–sector unit is calculated by dividing its direct CO_2 emissions by its gross output:

$$e_i = \frac{q_i}{x_i} \tag{2}$$

where q_i and x_i denote the direct CO_2 emissions and gross output of region–sector i, respectively. For region–sector units with zero gross output, the corresponding emission intensity is set to zero.

The CO_2 emissions embodied in regional final demand are then estimated as:

$$\mathbf{E} = \hat{\mathbf{e}}\mathbf{L}\mathbf{F} \tag{3}$$

where $\hat{\mathbf{e}}$ is the diagonal matrix of direct CO_2 emission intensities, $\mathbf{F}$ is the regional final demand matrix, and $\mathbf{E}$ is the embodied CO_2 emissions matrix. Each element E_{is} represents the CO_2 emissions generated in region–sector i to satisfy the final demand of region s, including emissions associated with both direct and indirect production activities throughout the supply chain. This framework links the location where emissions are generated to the region whose final demand ultimately drives those emissions.

2.4 Embodied Carbon Flow Measurement

The sector-level embodied emissions obtained from the EE-MRIO model were aggregated to the country level to construct an interregional embodied carbon flow matrix. The carbon flow from producing region r to final-demand region s is calculated as:

$$G_{rs} = \sum_{i \in r} E_{is} \tag{4}$$

where E_{is} denotes the emissions generated in region–sector i to satisfy the final demand of region s. Thus, G_{rs} represents the CO_2 emissions generated in region r but

driven by the final demand of region s. The rows of the matrix indicate the locations where emissions are generated, while the columns indicate the destinations of final demand. Diagonal elements represent emissions associated with domestic final demand, whereas off-diagonal elements represent embodied carbon flows between regions.

The first 60 rows and columns of the resulting 61×61 matrix were retained to examine embodied carbon flows among BRI countries. The ROW region remained in the full model to account for supply-chain linkages between BRI countries and non-BRI economies.

3 Results and Discussion

3.1 Consumption- and Production-Based Emissions among BRI Countries

Figure 1 presents the ten BRI countries with the highest CBE and PBE in 2015 and 2023. CBE is calculated by summing each column of the embodied carbon flow matrix and represents the emissions generated within the BRI system to satisfy a country's final demand. PBE is obtained by summing each row and represents the emissions generated within a country to satisfy final demand across the BRI countries. Because these estimates are derived from the 60×60 BRI carbon flow matrix, they exclude embodied carbon flows between BRI countries and the Rest of the World.

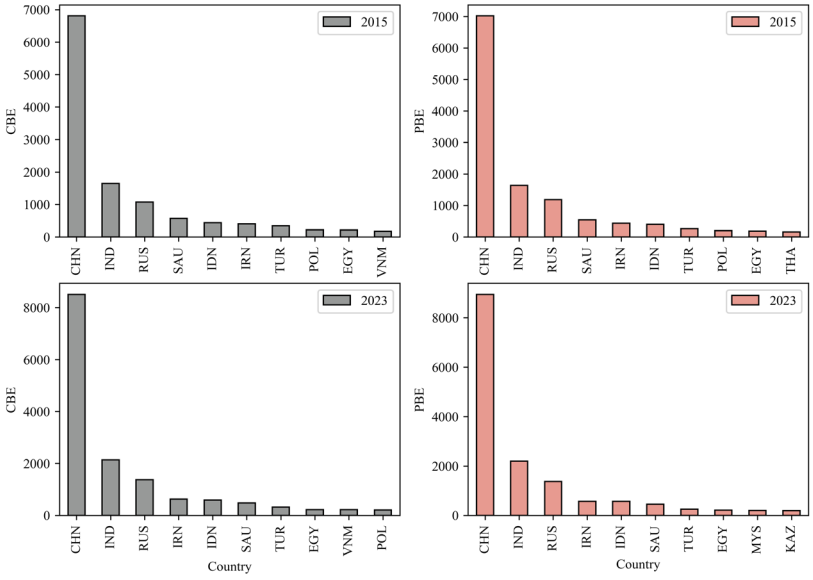


Fig. 1. Top ten BRI countries by CBE and PBE in 2015 and 2023. Note: CBE and PBE cover embodied carbon flows among the 60 BRI countries and exclude flows involving the Rest of the World. Unit: Mt CO_2eq.

The results show that intra-BRI embodied carbon was highly concentrated in a few large economies. The results reveal that intra-BRI embodied carbon was highly concentrated. China had by far the highest CBE and PBE in both years. In 2015, China's CBE was approximately 6,800 Mt CO_2eq, while its PBE was about 7,000 Mt CO_2eq. India and Russia ranked second and third, but their emission levels were substantially lower than those of China. Saudi Arabia, Indonesia, Iran, Türkiye, Poland, and Egypt also appeared among the ten largest emitters under both accounting approaches. This pattern highlights the dominant roles of large economies and major industrial and energy producers in BRI production and consumption networks. The concentration became more pronounced by 2023. China's CBE increased to approximately 8,500 Mt CO_2eq, while its PBE reached nearly 9,000 Mt CO_2eq. India's CBE and PBE both exceeded 2,000 Mt CO_2eq, and Russia remained the third-largest country under both measures. Iran and Indonesia also recorded notable increases and moved ahead of Saudi Arabia in the rankings. These changes suggest that the expansion of final demand and production activities in major BRI economies was accompanied by a substantial increase in supply-chain-related emissions.

The composition of the top ten countries was generally stable, although some differences emerged between CBE and PBE. In 2023, Viet Nam and Poland entered among the leading countries in CBE, reflecting the importance of their final demand in driving emissions within BRI supply chains. By contrast, Malaysia and Kazakhstan entered the top ten for PBE, indicating their relatively stronger roles as production locations serving final demand in other BRI countries. Similarly, Thailand appeared in the 2015 PBE ranking but not in the corresponding CBE ranking. These differences demonstrate that the geographical distribution of consumption-driven emissions does not fully coincide with that of production-related emission burdens.

3.2 Net Embodied Carbon Balance among BRI Countries

Figure 2 compares the proportions of net embodied carbon-importing and exporting countries within the BRI system in 2015 and 2023. Countries with CBE exceeding PBE are classified as net carbon importers, while those with PBE exceeding CBE are classified as net carbon exporters. In 2015, net carbon importers accounted for 78.3% of the 60 BRI countries, compared with 21.7% for net exporters. In 2023, the respective shares were 76.7% and 23.3%.

The results indicate that most BRI countries relied on emissions generated in other BRI economies to satisfy their final demand, while production-related emissions were concentrated in a relatively small group of net-exporting countries. The slight increase in the share of net exporters suggests a limited shift in the distribution of production-related carbon burdens between 2015 and 2023. However, these percentages represent the number of countries in each category rather than their shares of total embodied carbon flows, and they exclude flows involving the Rest of the World.

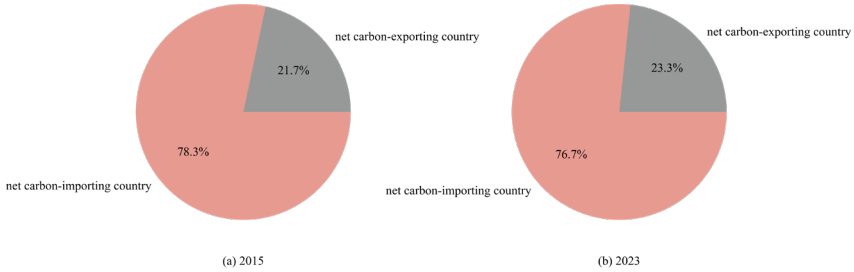


Fig. 2. Shares of BRI countries classified as net embodied carbon importers and exporters in 2015 and 2023. A positive CBE–PBE balance indicates a net embodied carbon importer, whereas a negative balance indicates a net embodied carbon exporter.

3.3 China's Embodied Carbon Linkages with BRI Countries

Figure 3 presents China's ten largest embodied carbon import sources and export destinations among BRI countries in 2015 and 2023. Embodied carbon imports refer to emissions generated in other BRI countries to satisfy China's final demand, whereas embodied carbon exports refer to emissions generated in China to satisfy the final demand of other BRI countries. The results therefore describe China's bilateral embodied carbon linkages within the BRI system and exclude flows involving the Rest of the World.

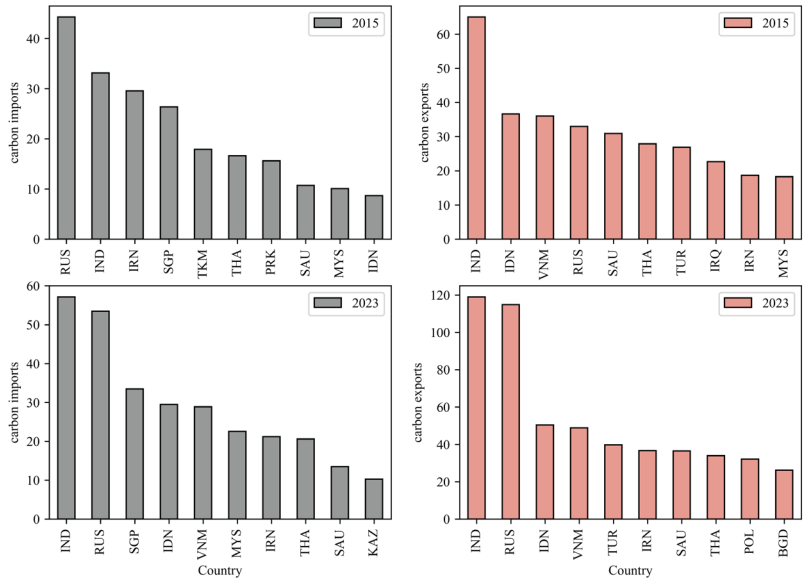


Fig. 3. China's ten largest embodied carbon import sources and export destinations among BRI countries in 2015 and 2023.

In 2015, Russia was China's largest source of embodied carbon imports, followed by India, Iran, and Singapore. By 2023, India had become the largest source, with Russia ranking second, while Singapore, Indonesia, and Vietnam also contributed substantially. Embodied carbon imports from India and Russia increased noticeably over the study period. These patterns may be associated with China's demand for energy, raw materials, intermediate inputs, and carbon-intensive products supplied by major BRI economies.

India was the largest destination for China's embodied carbon exports in both years. In 2015, it was followed by Indonesia, Vietnam, and Russia, while in 2023 Russia rose to second place, followed by Indonesia and Vietnam. China's embodied carbon exports to India and Russia increased particularly strongly between 2015 and 2023. This growth indicates that final demand in these economies played an increasingly important role in driving production and associated emissions in China. Overall, the bilateral results highlight China's dual position as both a major consumer of carbon-intensive products from other BRI countries and an important production center serving their final demand.

Table 1. Domestic contribution to China's intra-BRI emissions

Indicator	2015	2023	Change
Domestic emissions as a share of China's CBE	96.03%	95.79%	-0.24
Domestic-demand-driven emissions as a share of China's PBE	93.13%	91.14%	-1.99

Despite these cross-border linkages, China's intra-BRI carbon emissions remained predominantly domestic (Table 1). Emissions generated in China for its own final demand accounted for 96.03% of China's CBE in 2015 and 95.79% in 2023. Meanwhile, China's own final demand accounted for 93.13% of its PBE in 2015, decreasing to 91.14% in 2023. The relatively small decline in the domestic share of CBE indicates a modest increase in China's reliance on emissions generated in other BRI countries. The larger decline in the domestic-demand share of PBE suggests that final demand from other BRI countries became increasingly important in driving emissions generated in China.

4 Conclusion

This study applied an environmentally extended multi-regional input–output model to examine embodied carbon flows among 60 BRI countries in 2015 and 2023. Based on the EMERGING V2 database and its sector-level CO_2 inventory, CBE, PBE, net embodied carbon balances, and China's bilateral carbon linkages were evaluated. The results reveal that intra-BRI embodied carbon flows were highly concentrated. China recorded the highest CBE and PBE in both years, followed by other major economies such as India and Russia. The substantial growth in emissions among several leading economies indicates the increasing importance of final demand, industrial production, and regional supply-chain connections in shaping the BRI carbon footprint.

Most BRI countries were net embodied carbon importers. On a country-count basis, net importers fell marginally from 78.3% to 76.7% between 2015 and 2023, while net exporters rose from 21.7% to 23.3%. The distribution thus remained broadly stable, indicating that production-side burdens stayed concentrated in a few manufacturing-, resource-, and energy-intensive economies, with only a limited shift in the geography of emission-intensive production.

China played a dual role as both a major final-demand market and a central production hub. Russia, India, Iran, and Singapore were important sources of China's embodied carbon imports, while India remained its largest embodied carbon export destination. China's emissions were nevertheless predominantly driven by domestic production and demand. Domestic emissions accounted for approximately 96% of China's intra-BRI CBE in both years, whereas the domestic-demand share of its PBE declined from 93.13% to 91.14%. This decline indicates the growing influence of other BRI countries' final demand on emissions generated in China.

These findings highlight the need for coordinated carbon mitigation across BRI supply chains. Major producing economies should accelerate energy transition and improve industrial efficiency, while major consuming economies should address the upstream emissions associated with their final demand. Technology transfer, cleaner energy investment, and shared supply-chain carbon-accounting standards could support a more equitable distribution of mitigation responsibilities. However, the analysis covers embodied carbon flows among BRI countries only and excludes direct flows involving the Rest of the World. Future research could incorporate global linkages, sector-specific pathways, economic and population normalization, and structural decomposition to identify the drivers of observed changes more precisely.

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