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International trade, economic structure and embodied carbon responsibility in Belt and Road Initiative countries: a multi-regional input-output analysis

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Abstract. Climate responsibility is increasingly shaped by international trade, as production and final consumption are geographically separated across global value chains. This study investigates the relationship between economic structure, international trade, and embodied carbon responsibility among Belt and Road Initiative (BRI) countries using a multi-regional input-output framework. Consumption-based carbon emissions, embodied carbon exports and imports, sectoral carbon flows, and bilateral embodied carbon transfers are examined, with particular attention to changes between 2015 and 2023. The results reveal substantial heterogeneity in the carbon roles of BRI economies. South Korea, Saudi Arabia, Indonesia, Türkiye, and Iran exhibit relatively high consumption-based emissions, while China remains the largest net exporter of embodied carbon. Iran shows the most pronounced increase in net embodied carbon exports, whereas Pakistan experiences a substantial rise in net embodied carbon imports. Sectorally, energy processing and utilities, basic metals, non-metallic mineral products, chemicals, and transport-related activities constitute major sources of embodied carbon. The 2023 bilateral network is highly concentrated, with China–South Korea and Iran–Pakistan representing particularly large carbon-transfer pathways. These findings demonstrate that carbon responsibility within the BRI is distributed across interconnected production, trade, and consumption networks rather than being confined to national territorial emissions. Integrating production- and consumption-based accounting with trade and sectoral perspectives can support more differentiated and coordinated low-carbon strategies.

Keywords: Belt and Road Initiative, embodied carbon, consumption-based emissions, international trade, carbon responsibility, multi-regional input-output analysis

1. Introduction

Climate change has become one of the defining environmental and economic challenges of the twenty-first century. Carbon Dioxide (CO_2) emissions are closely associated with energy consumption, industrial production, transportation, and economic development, yet their distribution across countries is highly uneven. Differences in economic scale, industrial specialization, energy endowments, technological development, and

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consumption patterns lead countries to occupy different positions within the global carbon system [1]. Understanding these differences is important for international climate governance because national emissions do not necessarily correspond to the emissions generated to satisfy domestic consumption [2, 3].

Conventional production-based carbon accounting attributes emissions to the territory where production takes place. Although this approach provides a consistent basis for national inventories and climate commitments, it may obscure the role of international trade in redistributing emissions [3, 4]. As global value chains have expanded, production has become increasingly fragmented across countries, with products consumed in one economy often requiring raw materials, energy, intermediate goods, and manufacturing activities from several others. Consequently, emissions generated in exporting countries may be driven by consumption demand in importing countries [5, 6]. International trade can therefore create a spatial separation between the location of production and environmental impacts, with a substantial share of global CO_2 emissions associated with international supply chains [7, 8]. This has important implications for climate policy because territorial mitigation efforts may not fully capture emissions embodied in imported products.

Consumption-based carbon accounting provides a complementary perspective by allocating emissions to final demand rather than the location of production. Emissions embodied in imported goods and services are included in a country's carbon footprint, while emissions associated with exports are attributed to foreign demand [3, 9]. Comparing production-based and consumption-based emissions therefore provides insight into the spatial separation between production and consumption and helps identify countries that function as net exporters or importers of embodied carbon [5, 10].

This perspective is particularly relevant to the Belt and Road Initiative (BRI), which has promoted infrastructure development, international trade, energy cooperation, industrial investment, and economic connectivity across Asia, Europe, Africa, and other regions since its launch in 2013. BRI economies are highly heterogeneous: China is a major manufacturing and trade center; countries in Central Asia and the Middle East possess substantial energy and resource endowments; while economies in South and Southeast Asia have experienced rapid growth in consumption, industrial production, and international trade. These structural differences contribute to substantial variations in the generation and transfer of embodied carbon across the region [11, 12]. Resource-rich countries may export energy and raw materials to manufacturing economies, while consumption-oriented economies may increasingly rely on imported products and energy. Carbon responsibility is therefore distributed across interconnected production, trade, and consumption networks rather than being confined to the territory where emissions physically occur [11, 13, 14].

Multi-Regional Input-Output (MRIO) analysis has become an important approach for tracing direct and indirect environmental impacts through international production networks [15, 16]. Environmentally extended MRIO models link emissions generated at different stages of production chains to final demand, allowing both direct and upstream emissions associated with international supply chains to be quantified [17, 18]. The development of global MRIO databases has further improved the ability to trace environmental impacts across increasingly complex value chains, including indirect emissions generated through upstream suppliers and intermediate inputs [18, 19]. Such an approach is particularly valuable for economies deeply integrated into global production networks.

However, national carbon balances may conceal substantial differences among economic sectors and bilateral trade relationships. Existing BRI studies have demonstrated considerable heterogeneity in embodied carbon transfers across countries, sectors, and trade relationships [11-13]. The concentration of carbon transfers in major manufacturing and resource-related economies further suggests that national carbon positions are closely connected to countries' roles within regional and global value chains [11, 14]. Moreover, producer- and consumer-based perspectives can assign substantially different carbon responsibilities to

countries, while changes in industrial structures and participation in regional value chains may alter their positions as carbon exporters or importers over time [2, 4, 6, 11].

Against this background, this study uses an MRIO framework to examine embodied carbon responsibility among BRI countries from national, temporal, sectoral, and bilateral perspectives. The analysis focuses on consumption-based carbon emissions, changes in net embodied carbon trade between 2015 and 2023, sectoral contributions to embodied carbon flows, and major bilateral carbon-transfer pathways in 2023. By integrating these dimensions, the study assesses how economic structure and international trade shape the distribution of embodied carbon responsibility within BRI economic networks and provides insights for coordinated low-carbon development.

2. Material and method

2.1. MRIO framework

This study employs a Multi-Regional Input-Output (MRIO) framework to quantify carbon emissions associated with production, final consumption, and international trade among BRI countries. The MRIO framework represents economic transactions between countries and sectors and allows the direct and indirect emissions associated with final demand to be traced through global production chains [16, 19].

The MRIO framework represents economic transactions between countries and sectors and allows the direct and indirect emissions associated with final demand to be traced through global production chains. Let A denote the matrix of inter-industry input coefficients and L denote the Leontief inverse (Equation (1)):

$$L = (I - A)^{-1} \quad (1)$$

where I is the identity matrix.

Let F represent the vector of direct CO_2 emission coefficients. Total emissions embodied in final demand can then be expressed as (Equation (2)):

$$E = FLY \quad (2)$$

where Y represents the final demand matrix. This formulation captures not only direct emissions generated by final-demand sectors but also upstream emissions occurring throughout domestic and international supply chains [18, 20, 22].

2.2. Consumption-based carbon emissions and embodied carbon trade

Consumption-based carbon emissions are calculated by allocating emissions to the location of final demand. In contrast to production-based accounting, this approach includes emissions embodied in imported goods and services while excluding emissions associated with exports that ultimately satisfy foreign demand [5, 9].

For each country *i*, embodied carbon exports are calculated as the emissions generated within country *i*'s production system to satisfy final demand in other countries. Similarly, embodied carbon imports represent emissions generated outside country *i* that are associated with final demand within country *i*. This approach is consistent with established methods for assessing carbon embodied in international trade [5, 10].

Net embodied carbon trade is then calculated as: Net embodied carbon trade = Embodied carbon exports − Embodied carbon imports.

A positive value indicates that a country is a net embodied carbon exporter, while a negative value indicates that it is a net embodied carbon importer. This measure links carbon emissions to international

economic relationships rather than considering national emissions independently and provides an indicator of countries' positions within international carbon-transfer networks [4, 5].

2.3. Temporal, sectoral, and bilateral analysis

The analysis covers 2015 and 2023, allowing changes in national carbon roles to be identified over time. Countries are ranked according to consumption-based emissions and net embodied carbon exports and imports. Sectoral decomposition is conducted for embodied carbon emissions associated with exports and imports, with particular attention given to energy processing and utilities, basic metals and metal products, non-metallic mineral products, chemical products, machinery and electrical equipment, and transport-related activities. Such sectoral decomposition is consistent with previous MRIO-based research showing that energy-, manufacturing-, mineral-, and resource-intensive industries constitute major sources of embodied carbon in international trade [11, 12, 21].

Finally, bilateral embodied carbon flows are examined for 2023 to identify major source–destination relationships and the structural characteristics of the BRI carbon network. Previous network-based studies have demonstrated the value of examining bilateral carbon flows for understanding the structural characteristics of embodied carbon transfers [13, 14].

3. Result

3.1. Cross-country differences in consumption-based carbon emissions

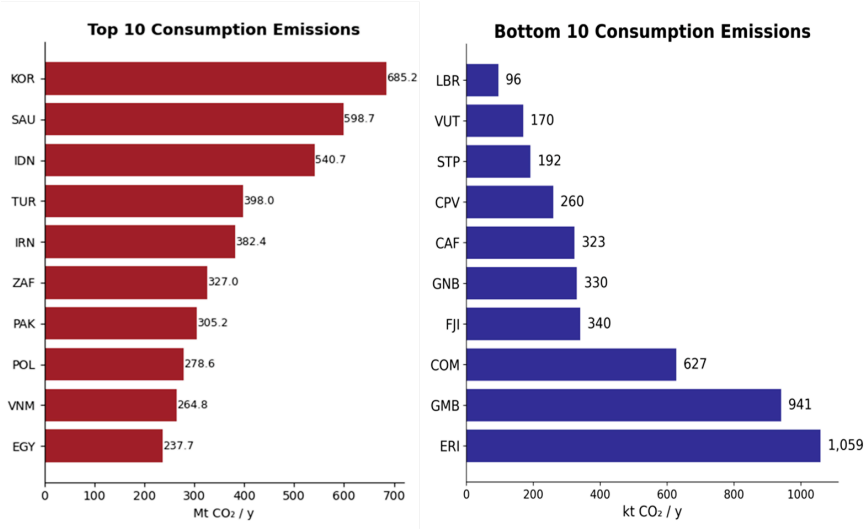


Figure 1. Top and bottom 10 BRI countries by consumption-based CO_2 emissions

Consumption-based carbon emissions show substantial differences among BRI countries, reflecting variations in economic scale, industrialization, energy demand, and consumption patterns (Figure 1). The countries with the highest consumption-based emissions include South Korea, Saudi Arabia, Indonesia, Türkiye, and Iran. South Korea records the highest value at approximately 685 Mt CO_2/y, followed by Saudi Arabia, Indonesia, Türkiye, and Iran.

The relatively high consumption-based emissions of these economies reflect different combinations of economic and structural factors. In South Korea and Türkiye, large manufacturing sectors and strong integration into international production networks generate substantial energy and material requirements. Saudi Arabia and Iran, in contrast, have carbon-intensive economic structures closely associated with fossil fuel production, energy use, and resource-intensive activities. Indonesia combines a large domestic economy with substantial energy and industrial demand.

At the opposite end of the distribution, Laos, Vanuatu, and São Tomé and Príncipe exhibit substantially lower consumption-based emissions. Their relatively low values are primarily associated with smaller economic scales, limited industrial capacity, and lower overall energy demand.

This contrast demonstrates that consumption-based carbon emissions are not determined by economic size alone. The composition of economic activity and the structure of energy and trade systems also play an important role. In particular, countries with strong manufacturing, resource extraction, or consumption demand can exhibit high carbon footprints through different mechanisms [3, 10].

3.2. Net embodied carbon exporters and importers

3.2.1. Net carbon-exporting countries

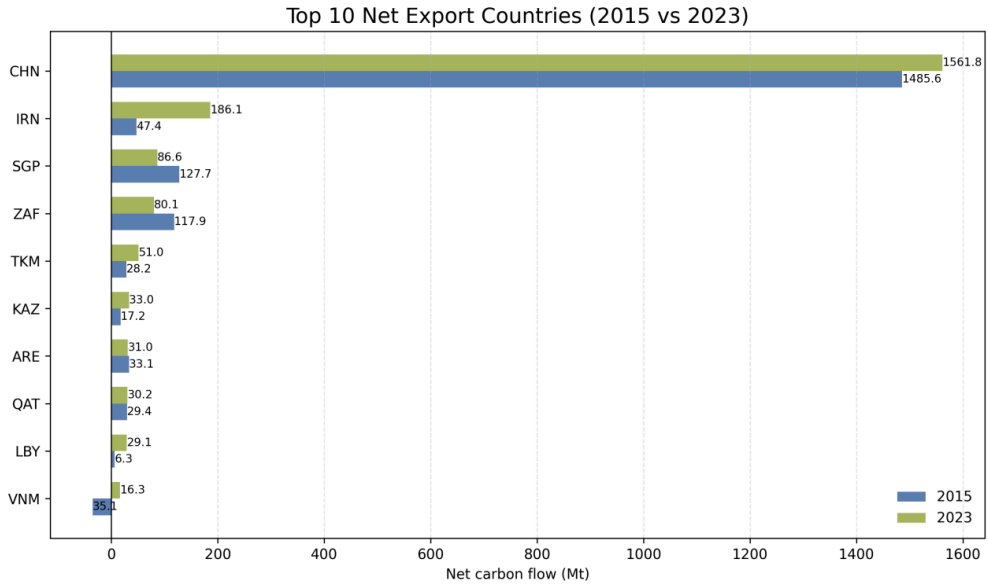


Figure 2. Top 10 net embodied carbon-exporting countries, 2015 vs. 2023

Figure 2 presents the top 10 net embodied carbon-exporting BRI countries in 2015 and 2023. The comparison reveals substantial changes in the net embodied carbon positions of BRI economies over the study period, although China remained by far the largest net exporter. The persistence of these differences reflects the heterogeneous economic structures, energy systems, and positions of BRI countries within international production and trade networks [5, 11].

China remained the dominant net embodied carbon exporter, with net embodied carbon exports increasing from approximately 1,485.6 Mt CO_2/y in 2015 to 1,561.8 Mt CO_2/y in 2023. China's persistent position as the largest net exporter reflects the scale and complexity of its manufacturing and industrial production system. Its production networks encompass energy supply, heavy industry, metals, chemicals, machinery, electrical equipment, and a wide range of intermediate and manufactured goods. As a major participant in global and

regional value chains, China generates substantial emissions that become embodied in goods subsequently exported to other economies. This pattern is consistent with previous research identifying China as a major contributor to carbon emissions embodied in international trade and highlighting the importance of China's manufacturing structure in regional carbon transfers [6, 11, 12].

Iran experienced the most pronounced increase among the major net embodied carbon exporters. Its net embodied carbon exports increased from 47.4 Mt CO_2/y in 2015 to 186.1 Mt CO_2/y in 2023. Turkmenistan and Kazakhstan also recorded substantial increases, from 28.2 Mt and 17.2 Mt CO_2/y in 2015 to 51.0 Mt and 33.0 Mt CO_2/y in 2023, respectively. The increasing net carbon-export positions of these economies highlight the role of resource endowments and energy-intensive production within the BRI carbon network. Countries with substantial fossil-fuel and mineral resources can generate significant embodied emissions through extraction, processing, energy production, and related industrial activities, particularly when these outputs are directed toward external demand [11, 12].

By contrast, Singapore and South Africa experienced declines in net embodied carbon exports. Singapore's value decreased from 127.7 Mt CO_2/y in 2015 to 86.6 Mt CO_2/y in 2023, while South Africa declined from 117.9 Mt CO_2/y to 80.1 Mt CO_2/y. These changes suggest that a country's position within embodied carbon trade is not necessarily fixed but may evolve with changes in industrial composition, trade patterns, domestic demand, and participation in regional value chains. Previous studies similarly emphasize that changes in production and trade structures can alter the distribution of emissions embodied in international trade over time [6, 10].

Vietnam provides an especially notable example of such structural change. Its net embodied carbon balance shifted from −35.1 Mt CO_2/y in 2015, indicating a net embodied carbon-importing position, to 16.3 Mt CO_2/y in 2023, making it a net exporter. This transition is consistent with Vietnam's increasing integration into regional manufacturing and export-oriented production networks. More generally, the movement of countries between net importing and exporting positions illustrates how industrial development and changing roles within international value chains can reshape the geographical distribution of embodied carbon responsibility [6, 10].

Overall, the results indicate that net embodied carbon exports are concentrated among countries with large manufacturing systems, substantial resource endowments, or important positions within regional production networks. However, the changes observed between 2015 and 2023 demonstrate that these positions can evolve considerably over time. The results therefore support the view that embodied carbon responsibility should be understood as a dynamic outcome of economic structure, production specialization, and international trade rather than as a fixed characteristic determined solely by territorial emissions [4, 5].

3.2.2. Net carbon-importing countries

The net-import side reveals a different pattern from the major net-exporting economies (Figure 3). Pakistan experienced the most substantial increase in net embodied carbon imports, rising from 35.0 Mt CO_2/y in 2015 to 125.5 Mt CO_2/y in 2023. Pakistan consequently became the largest net embodied carbon importer among the countries examined in 2023. This increase suggests a growing dependence on carbon embodied in foreign production and trade, particularly as domestic economic activity and demand become increasingly connected to regional production networks.

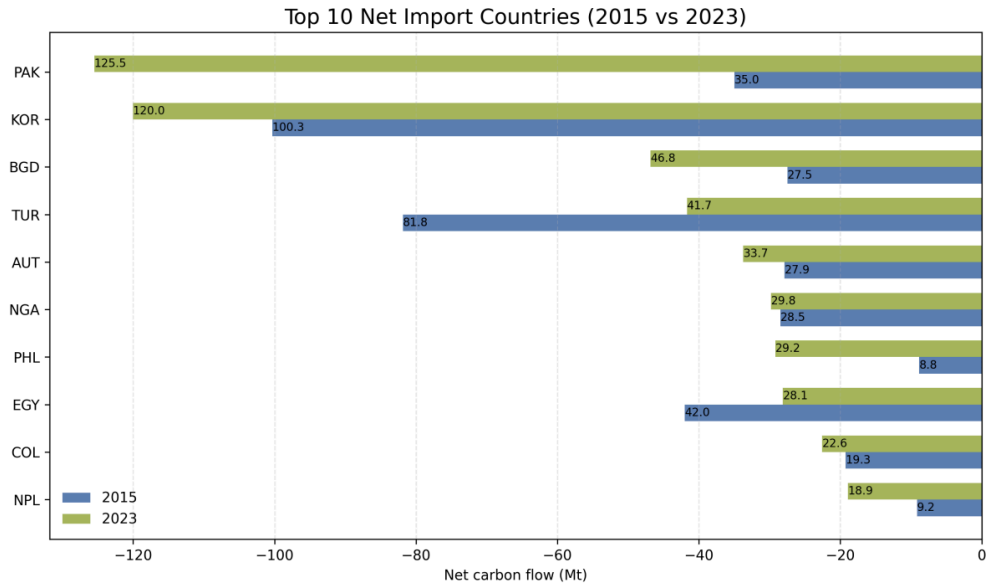


Figure 3. Top 10 net embodied carbon-importing countries, 2015 vs. 2023

South Korea also experienced an increase in net embodied carbon imports, from 100.3 Mt CO_2/y in 2015 to 120.0 Mt CO_2/y in 2023. This result is particularly notable because South Korea simultaneously records high consumption-based emissions and has a highly developed manufacturing sector. The coexistence of substantial domestic production and significant net embodied carbon imports illustrates the complexity of carbon responsibility in highly integrated economies, where domestic consumption can depend on emissions generated through overseas production and imported intermediate inputs [3, 9].

The coexistence of high consumption-based emissions and high net embodied carbon imports suggests that part of South Korea's carbon footprint occurs outside its territorial boundaries. This finding illustrates why production-based emissions alone may provide an incomplete representation of carbon responsibility in highly globalized economies. Consumption-based accounting captures emissions associated with goods and services consumed domestically regardless of where those emissions are physically generated, thereby providing a complementary perspective on national carbon footprints [2, 5, 10].

Bangladesh, the Philippines, and Nepal also recorded increasing net embodied carbon imports. Their values increased from 27.5 Mt, 8.8 Mt, and 9.2 Mt CO_2/y in 2015 to 46.8 Mt, 29.2 Mt, and 18.9 Mt CO_2/y in 2023, respectively. These increases indicate a strengthening connection between domestic demand and overseas production. As economies become more integrated into international markets, imported manufactured goods, energy, construction materials, and intermediate products may embody substantial emissions generated outside national borders [3, 5].

These changes indicate that expanding domestic demand is increasingly connected to overseas production. The resulting separation between the location of production and the location of consumption is a central feature of global value chains and provides an important explanation for differences between production-based and consumption-based carbon emissions [6, 10]. For economies that rely heavily on imported energy, materials, and manufactured products, part of the emissions associated with domestic economic activity may therefore occur beyond national boundaries.

Türkiye and Egypt, however, experienced declining net embodied carbon imports. Türkiye declined from 81.8 Mt CO_2/y in 2015 to 41.7 Mt CO_2/y in 2023, while Egypt decreased from 42.0 Mt CO_2/y to 28.1 Mt CO_2/y. These declines indicate that the carbon balance of an economy can change over time as domestic

production capacity, industrial structure, energy systems, and trade relationships evolve. Changes in countries' participation in international production networks can consequently alter their positions as net embodied carbon exporters or importers [6, 11].

The contrasting trajectories among BRI countries demonstrate that embodied carbon positions are closely related to changes in economic structure, domestic production capacity, energy systems, and trade patterns. The results further suggest that net embodied carbon imports should not necessarily be interpreted as an indicator of lower overall carbon responsibility; rather, they reveal the extent to which domestic consumption and economic activity are associated with emissions generated through international supply chains [4, 5].

3.3. Sectoral structure of embodied carbon trade

3.3.1. Sectoral characteristics including China

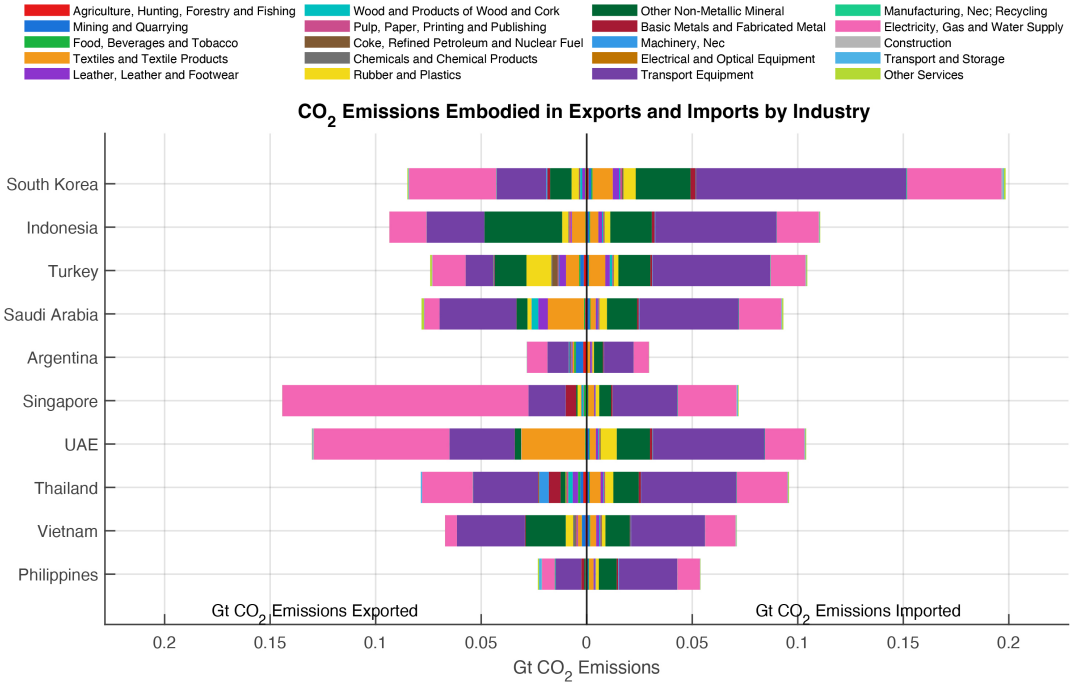


Figure 4. CO_2 emissions embodied in exports and imports by industry

Figure 4 presents CO_2 emissions embodied in exports and imports across major industries. Sectoral analysis reveals that embodied carbon trade is highly concentrated in energy- and resource-intensive industries. Energy processing and utilities, basic metals and metal products, non-metallic mineral products, chemical products, and transport-related activities constitute major sources of embodied carbon. This concentration is consistent with previous MRIO-based research showing that energy supply, heavy industry, metals, minerals, and other resource-intensive sectors account for substantial shares of emissions embodied in international trade [11, 12].

China exhibits the most prominent sectoral emissions. In 2023, export-related embodied carbon from energy processing and utilities reached approximately 1,024.09 Mt CO_2, substantially exceeding emissions from other sectors. Basic metals and metal products and transport, postal, and travel services contributed approximately 250.34 Mt and 261.00 Mt CO_2, respectively.

These patterns reflect China's extensive industrial system and its position within international manufacturing networks. Energy production provides essential inputs to heavy industry, metals, chemicals, machinery, and downstream manufacturing, while emissions generated at upstream stages can subsequently become embodied in products exported to other economies. The concentration of embodied emissions in China's industrial sectors is consistent with the country's historically important role in global manufacturing and international trade [6, 11].

The concentration of embodied carbon in these sectors also indicates that international trade is closely connected to the structure of national energy systems. Economies specializing in energy-intensive industries are more likely to transfer substantial embodied emissions through exports, while countries dependent on imported energy and industrial inputs may absorb these emissions through imports. This reflects the broader relationship between industrial specialization, energy intensity, and the spatial distribution of emissions embodied in trade [3, 10].

3.3.2. Sectoral characteristics excluding China

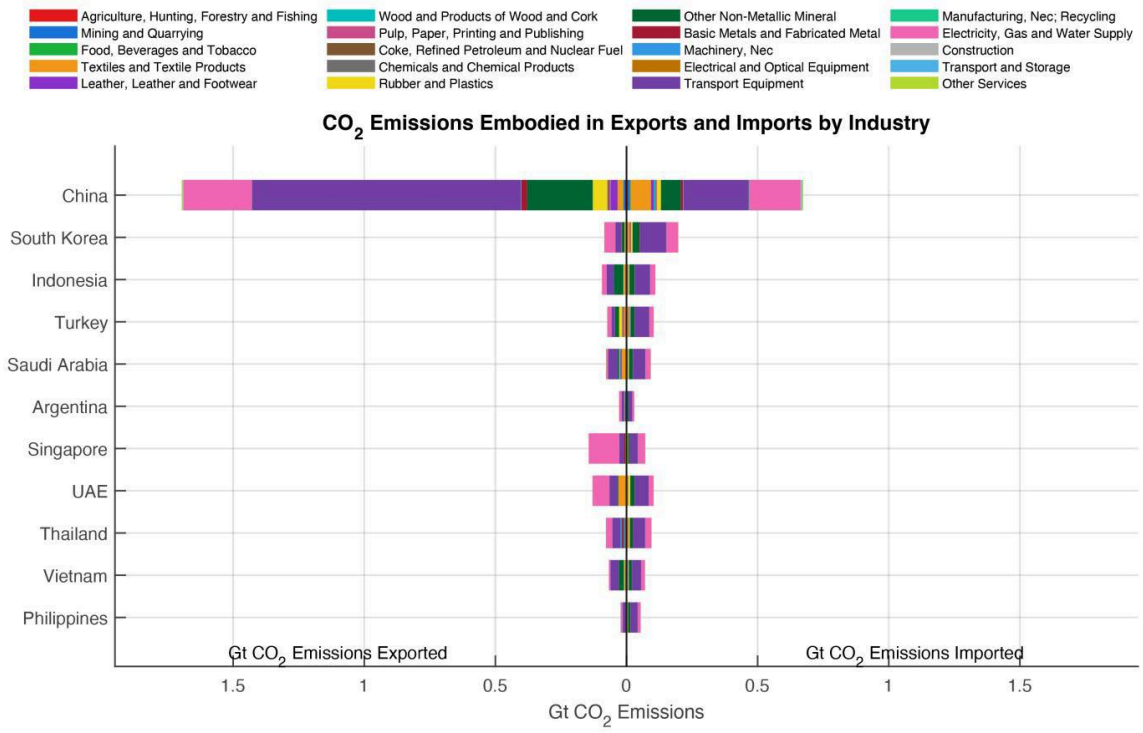


Figure 5. CO_2 emissions embodied in exports and imports by industry, excluding China

Figure 5 presents CO_2 emissions embodied in exports and imports by industry, excluding China. Excluding China provides a clearer comparison of the sectoral carbon characteristics of other BRI economies. The results show that embodied carbon emissions remain concentrated in energy processing, utilities, metals, minerals, chemicals, and transportation, but the relative importance of these sectors differs across countries. Such variation reflects differences in industrial specialization, resource endowments, energy structures, and participation in international production networks [11, 12].

South Korea, Türkiye, and Indonesia show relatively strong import-side embodied carbon emissions in energy-related sectors. In South Korea, embodied carbon associated with imports from energy processing and

utilities reached approximately 99.58 Mt CO_2, compared with 23.44 Mt CO_2 associated with exports from the same sector.

Türkiye and Indonesia also recorded substantial import-related embodied carbon in this sector, at approximately 55.67 Mt and 57.39 Mt CO_2, respectively.

These results suggest that the carbon footprint of domestic economic activity in these economies is partly dependent on foreign energy and intermediate inputs. Such dependence illustrates how international trade can shift part of the emissions associated with domestic consumption and production to external production locations [5, 9].

Resource-rich economies demonstrate a contrasting structure. Saudi Arabia and the United Arab Emirates show stronger carbon-export characteristics in mineral products, energy, and resource-intensive sectors. Embodied carbon emissions associated with exports from mineral and resource-related sectors reached approximately 29.99 Mt CO_2 in the UAE and 17.10 Mt CO_2 in Saudi Arabia. This pattern is consistent with the role of resource-based specialization in shaping embodied carbon exports, particularly where energy and mineral products constitute important components of international trade [11, 12].

Singapore represents another distinctive structure, with transport, postal, and travel services contributing approximately 116.66 Mt CO_2 to embodied carbon exports. This result reflects the importance of its international logistics and maritime activities and demonstrates that embodied carbon transfers are not limited to conventional manufacturing and resource-extraction sectors.

The sectoral results therefore demonstrate that embodied carbon responsibility is strongly conditioned by economic specialization. Resource exporters, manufacturing economies, logistics hubs, and consumption-oriented economies participate in the carbon network through different channels. This finding reinforces the importance of considering sectoral and structural characteristics when evaluating carbon responsibility within international production networks [4, 11, 15].

3.4. Major bilateral embodied carbon flows in 2023

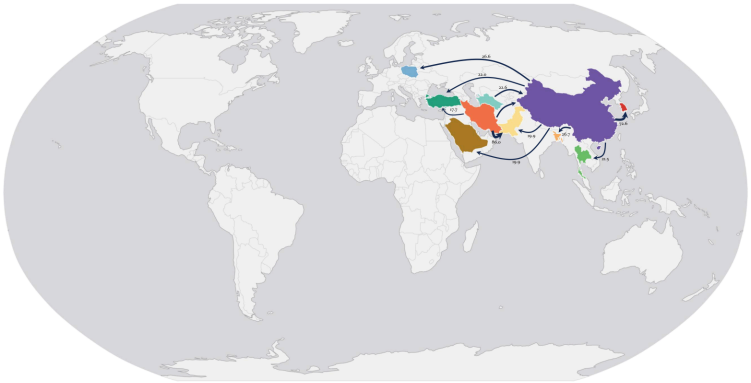


Figure 6. Major bilateral embodied carbon flows among BRI countries in 2023

Figure 6 presents the major bilateral embodied carbon flows among BRI countries in 2023. The bilateral embodied carbon network is highly concentrated, with a relatively small number of countries accounting for major cross-border carbon flows. China and Iran emerge as particularly important carbon-exporting nodes. This concentration is consistent with previous studies showing that embodied carbon transfers within the BRI form an interconnected but uneven network, with major manufacturing and resource-related economies occupying important positions within regional carbon-transfer networks [11, 13, 14].

The largest identified bilateral flow is from China to South Korea, reaching approximately 100.39 Mt CO_2. China also records substantial flows to Thailand, Saudi Arabia, Poland, Türkiye, and Pakistan, at approximately 42.08, 33.42, 30.14, 27.13, and 20.84 Mt CO_2, respectively.

These flows demonstrate China's central position within the BRI embodied carbon network. China acts as a major manufacturing and intermediate-goods supplier, meaning that emissions generated through domestic industrial production become embodied in products consumed or further processed abroad. This role is consistent with China's position as a major participant in global and regional production networks and its significant contribution to emissions embodied in international trade [6, 11].

Iran represents another major carbon-exporting node. Its embodied carbon flow to Pakistan reached approximately 86.07 Mt CO_2, while flows to China and Türkiye reached 44.55 Mt and 19.19 Mt CO_2, respectively. These flows indicate the importance of resource- and energy-intensive production in shaping regional carbon-transfer relationships and are consistent with the broader role of resource-rich economies as suppliers of carbon-intensive goods and energy within regional trade networks [11, 12].

The Iran–Pakistan pathway is particularly important because it illustrates the relationship between regional energy supply and downstream demand. Carbon emissions generated during energy- and resource-related production in Iran are embodied in goods and energy flows supporting economic activity in Pakistan. Such bilateral relationships demonstrate how the environmental impacts associated with production can be geographically separated from the economies in which related demand occurs [5, 10].

An important characteristic of the network is China's dual role. While China exports substantial embodied carbon to South Korea, Thailand, Türkiye, Pakistan, and other economies, it also receives significant embodied carbon flows from Iran and Turkmenistan, at approximately 44.55 Mt and 23.21 Mt CO_2, respectively.

China therefore functions not simply as a carbon exporter but also as an intermediary node linking upstream resource suppliers with downstream manufacturing and consumption markets. This multidirectional position highlights the networked nature of embodied carbon trade, in which countries can simultaneously participate as exporters, importers, producers, and consumers within different stages of regional value chains [13, 14].

This multidirectional structure demonstrates that embodied carbon does not move through a simple exporter-to-importer relationship. Instead, emissions can pass through multiple stages of regional value chains. A resource-exporting country may supply energy to a manufacturing economy, which subsequently exports carbon-intensive products to another economy. Carbon responsibility is consequently distributed across interconnected production and consumption relationships rather than being attributable exclusively to a single country [4, 5].

The major flows also display a clear East Asia–Middle East–South Asia connectivity pattern. East Asia represents a major manufacturing and consumption center; the Middle East and Central Asia provide important energy and raw materials; and South Asia increasingly represents an important downstream market. This regional structure demonstrates how differences in resource endowment, industrial specialization, and market demand combine to shape the geography of embodied carbon transfers within the BRI [11, 13].

4. Discussion

4.1. Economic structure and embodied carbon responsibility

The results demonstrate that embodied carbon responsibility among BRI countries is closely associated with differences in economic structure, resource endowment, and positions within international production

networks. Resource-rich economies, particularly in the Middle East and Central Asia, tend to function as net embodied carbon exporters because energy extraction and resource-intensive production constitute important components of their economies. In contrast, manufacturing-oriented economies such as China generate substantial embodied carbon through the production of industrial goods, intermediate inputs, and manufactured exports. Other economies with high consumption demand or substantial dependence on imported energy and intermediate products tend to exhibit stronger net embodied carbon imports. These patterns are consistent with the broader literature showing that the distribution of embodied carbon is strongly influenced by countries' economic specialization and positions within global production networks [4, 5, 10].

These differences indicate that national carbon roles cannot be interpreted solely according to territorial emissions. A country may generate substantial production-based emissions because it supplies goods and energy to external markets, while another country may have lower territorial emissions but rely heavily on carbon-intensive imports. The sectoral results further demonstrate that energy, metals, mineral products, chemicals, and transportation are important channels through which economic activity generates and transfers embodied carbon [2, 3, 11]. Therefore, economic specialization plays a central role in determining how carbon emissions are distributed across the BRI trade network.

4.2. Production–consumption separation and trade-related carbon responsibility

The comparison between consumption-based emissions and embodied carbon trade highlights a spatial separation between production and consumption within the BRI region. International trade allows carbon-intensive production to occur in one country while the resulting goods and services are ultimately consumed or used for further production elsewhere. This creates a difference between the location of emissions and the location of the demand that drives them, a phenomenon widely documented in the literature on consumption-based carbon accounting and carbon embodied in international trade [3, 6, 9].

The 2015–2023 comparison further shows that national carbon positions can change as countries undergo industrial restructuring and become more deeply integrated into regional value chains. Vietnam's transition from a net embodied carbon importer to exporter and the substantial increase in Pakistan's net carbon imports illustrate this dynamic process. These changes suggest that carbon responsibility should be viewed as an evolving relationship between production, consumption, and trade rather than as a fixed national characteristic [10, 11].

A combined production-, consumption-, and trade-based perspective can therefore provide a more comprehensive assessment of carbon responsibility. Such an approach is particularly relevant for the BRI because economic integration increasingly connects resource suppliers, manufacturing centers, and consumption markets through complex cross-border supply chains [12, 16].

4.3. Implications for BRI low-carbon cooperation

The findings suggest that low-carbon cooperation under the BRI should consider differentiated national economic functions. Resource-exporting countries can prioritize cleaner energy production, resource extraction, and processing, while manufacturing economies can focus on industrial energy efficiency, clean technologies, and low-carbon production. Countries with substantial embodied carbon imports can reduce their consumption-based footprints through cleaner energy systems, sustainable consumption, and greater attention to the carbon intensity of imported products. Such differentiated strategies are consistent with the concept of shared producer and consumer responsibility, which emphasizes that responsibility for environmental impacts can be distributed across international production and consumption systems rather than assigned exclusively to producers or consumers [2, 4].

More broadly, mitigation policies should extend beyond territorial emissions toward the management of carbon embodied in international trade. Supply-chain carbon accounting, carbon disclosure, green trade, and cooperation in low-carbon technologies could improve the transparency of cross-border emission transfers [5, 10]. Targeting major carbon-intensive sectors and bilateral trade corridors may also provide more effective mitigation opportunities than treating all countries and trade relationships uniformly, particularly given the uneven structure of BRI carbon-transfer networks [11, 13, 23].

5. Conclusion

This study applied a multi-regional input-output framework to examine consumption-based carbon emissions and embodied carbon trade among BRI countries from national, sectoral, temporal, and bilateral perspectives. The results reveal substantial differences in carbon roles across the region. Resource-rich and manufacturing-oriented economies tend to act as major embodied carbon exporters, while several consumption-oriented and import-dependent economies exhibit substantial embodied carbon imports.

The analysis also demonstrates that embodied carbon trade is strongly concentrated in energy-, resource-, manufacturing-, and transportation-related sectors and along major bilateral trade corridors. Changes between 2015 and 2023 further indicate that national carbon positions can evolve with changes in economic structure and participation in regional value chains. These findings highlight the importance of integrating production-based, consumption-based, and trade-related perspectives when evaluating carbon responsibility.

For the BRI, effective climate governance should therefore move beyond national territorial emissions and incorporate carbon transfers embedded in international supply chains. Differentiated mitigation strategies, combined with greater regional cooperation in green production, clean energy, carbon accounting, and sustainable trade, could help reduce carbon leakage and support a more coordinated and equitable low-carbon transition across the region.

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References

[1] Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., Barbero, L., … Zaehle, S. (2023). Global carbon budget 2023. *Earth System Science Data, 15*(12), 5301–5369. https: //doi.org/10.5194/essd-15-5301-2023

[2] Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics, 65*(1), 13–23. https: //doi.org/10.1016/j.ecolecon.2007.10.014

[3] Hertwich, E. G., & Peters, G. P. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science & Technology, 43*(16), 6414–6420. https: //doi.org/10.1021/es803496a

[4] Lenzen, M., Murray, J., Sack, F., & Wiedmann, T. (2007). Shared producer and consumer responsibility—Theory and practice. *Ecological Economics, 61*(1), 27–42. https: //doi.org/10.1016/j.ecolecon.2006.05.018

[5] Peters, G. P., & Hertwich, E. G. (2008). CO_2 embodied in international trade with implications for global climate policy. *Environmental Science & Technology, 42*(5), 1401–1407. https: //doi.org/10.1021/es072023k

[6] Peters, G. P., Minx, J. C., Weber, C. L., & Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences, 108*(21), 8903–8908. https: //doi.org/10.1073/pnas.1006388108

[7] Davis, S. J., Peters, G. P., & Caldeira, K. (2011). The supply chain of CO_2 emissions. *Proceedings of the National Academy of Sciences, 108*(21), 8903–8908. https: //doi.org/10.1073/pnas.1107409108

[8] Kanemoto, K., Moran, D., Lenzen, M., & Geschke, A. (2014). Mapping the carbon footprint of nations. *Environmental Science & Technology, 48*(19), 10512–10520.

[9] Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences, 107*(12), 5687–5692. https: //doi.org/10.1073/pnas.0906974107

[10] Sato, M. (2014). Embodied carbon in trade: A survey of the empirical literature. *Journal of Economic Surveys, 28*(5), 831–861. https: //doi.org/10.1111/joes.12027

[11] Lu, Y., Zhang, Y., Cao, X., Wang, C., Wang, Y., Zhang, M., & Da, Y. (2020). Imbalance and drivers of carbon emissions embodied in trade along the Belt and Road Initiative. *Applied Energy, 280*, 115934. https: //doi.org/10.1016/j.apenergy.2020.115934

[12] Zhang, Z., & Chen, W. (2022). Embodied carbon transfer between China and the Belt and Road Initiative countries. *Journal of Cleaner Production, 378*, 134569. https: //doi.org/10.1016/j.jclepro.2022.134569

[13] Lin, Z., Meng, F., Wang, D., Liao, D., Sun, Y., Hou, J., Liu, G., Giannetti, B. F., Agostinho, F., & Almeida, C. M. V. B. (2023). Unfolding carbon inequality across Belt and Road Initiative countries and regions under a global trade network. *Ecological Modelling, 482*, 110411. https: //doi.org/10.1016/j.ecolmodel.2023.110411

[14] Wang, Y., Zhang, R., Wang, S., Wang, L., Dai, X., & Zu, Z. (2025). Carbon flow tracking and network reconfiguration: A network evolution analysis of embodied carbon emissions from Belt and Road trade under regional and industry perspectives. *Frontiers in Sustainable Cities, 7*, 1617630. https: //doi.org/10.3389/frsc.2025.1617630

[15] Wiedmann, T. (2009). A review of recent multi-region input-output models used for consumption-based emission and resource accounting. *Ecological Economics, 69*(1), 211–222. https: //doi.org/10.1016/j.ecolecon.2009.08.026

[16] Tukker, A., & Dietzenbacher, E. (2013). Global multiregional input-output frameworks: An introduction and outlook. *Economic Systems Research, 25*(1), 1–19. https: //doi.org/10.1080/09535314.2012.761179

[17] Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-region input-output database at high country and sector resolution. *Economic Systems Research, 25*(1), 20–49. https: //doi.org/10.1080/09535314.2013.769938

[18] Wiedmann, T., & Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience, 11*, 314–321. https: //doi.org/10.1038/s41561-018-0113-9

[19] Minx, J. C., Wiedmann, T., Wood, R., Peters, G. P., Lenzen, M., Owen, A., Scott, K., Barrett, J., Hubacek, K., Baiocchi, G., Paul, A., Dawkins, E., Briggs, J., Guan, D., Suh, S., & Ackerman, F. (2009). Input-output analysis and carbon footprinting: An overview of applications. *Economic Systems Research, 21*(3), 187–216. https: //doi.org/10.1080/09535310903141295

[20] Andrew, R. M., & Peters, G. P. (2013). A multi-region input-output table based on the Global Trade Analysis Project database (GTAP-MRIO). *Economic Systems Research, 25*(1), 99–121.

[21] Jiang, W., Mukhopadhaya, P., & Zhang, H. (2025). An exploration of the effect of Belt and Road Initiative on carbon emissions embodied in China's manufacturing industry exports. *Scientific Reports, 15*, 6983. https: //doi.org/10.1038/s41598-025-90602-2

[22] Lenzen, M., Pade, L.-L., & Munksgaard, J. (2004). CO_2 multipliers in multi-region input-output models. *Economic Systems Research, 16*(4), 391–412. https: //doi.org/10.1080/0953531042000304272

[23] Zhang, L., Zhao, W., Chiu, Y.-H., Zhang, L., Shi, Z., & Shi, C. (2024). Deep mitigation for trade-embodied carbon emissions among the Belt and Road Initiative countries. *iScience, 27*(8), 110054. https: //doi.org/10.1016/j.isci.2024.110054