



Environmental Effects of China's BRI Outward FDI: Accounting for Embodied Carbon Flows and Consumption-Based Emission Responsibility

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Abstract. This study is based on the multi-regional input-output model (MRIO) with environmental expansion, utilizing the CEADs database to calculate carbon flows in 49 core countries along the Belt and Road. It reveals the environmental effects of China's investments in these countries from the perspective of implicit carbon flows and carbon emission responsibilities. The findings indicate that regional carbon flows exhibit a "core-periphery" structure, where China, as the core net producer, bears significant carbon transfer responsibilities, while developed consumer countries like Germany outsource substantial carbon footprints. The carbon roles of each country are closely related to their industrial development models, posing differentiated carbon lock-in risks. The study calls for establishing a shared responsibility mechanism based on the linkage between consumption and investment sides to promote green and low-carbon coordinated development along the Belt and Road.

Keywords: Belt and Road; Implied carbon flow; Carbon emission responsibility; Multi-regional input-output model

1 Introduction

In recent decades, global climate change has emerged as the most pressing challenge to human survival and development, primarily driven by anthropogenic greenhouse gas emissions, particularly carbon dioxide (CO₂). According to the Intergovernmental Panel on Climate Change (IPCC) report, the global average temperature has risen by approximately 1.1°C compared to pre-industrial levels, triggering a series of cascading effects. To address this critical trend, the international community reached the landmark Paris Agreement in 2015, setting long-term goals to limit global temperature rise to within 2°C or even 1.5°C. Carbon emissions not only directly contribute to global warming but also pose profound and unequal threats to water resources, food security, and public health through crises such as rising sea levels and frequent extreme weather events (Mahuaqing Zuo & Shasha Yu, 2025). Therefore, accurate carbon emission accounting and clarifying its generation and transfer mechanisms in international trade

have become crucial scientific foundations for formulating effective mitigation and adaptation policies, as well as advancing global climate governance toward fairness and equity.

In this global context, the Belt and Road Initiative covers numerous emerging economies and developing countries at critical stages of industrialization and urbanization. Their economic growth is accompanied by robust energy consumption and infrastructure development demands, while also becoming a major source of global carbon emission increments (Xu R, Tong D, Xiao Q., et al., 2024). This region accounts for a significant proportion of global manufacturing production, yet its carbon emission intensity exceeds the world average, making the need for green transition extremely urgent. Meanwhile, the process of globalization has tightly interconnected national economies through complex global value chains, meaning a country's carbon emissions are no longer solely determined by its domestic production methods but are deeply tied to global consumption demands, thereby generating "hidden carbon" that is transferred across borders alongside international trade (Zhao Shuyuan et al., 2025). This "carbon leakage" phenomenon leads to a mismatch between the geographical distribution of carbon emissions and the responsibilities for emission reduction, posing a key challenge in global climate governance.

In the face of challenges, the major participating countries in the Belt and Road Initiative have successively demonstrated policy willingness to promote green development. As a globally significant economy, China proposed the initiative to build a green Belt and Road in 2017 and clarified its "dual carbon" goals in 2020. Similarly, Russia, as a major energy producer, has also released a low-carbon development strategy targeting 2060 (Zou Lina et al., 2025). These adjustments in national strategies highlight the practical needs and potential opportunities for coordinated low-carbon transition under the Belt and Road framework. As the region's primary source of infrastructure construction and direct investment, China's investment activities are one of the key factors driving energy consumption, industrial upgrading, and changes in trade patterns among countries along the route, thereby influencing regional carbon emission dynamics. Therefore, focusing on Belt and Road countries and systematically studying their carbon footprints and implicit carbon flows from a consumption-side perspective is of significant theoretical and practical importance for objectively assessing countries' actual emission responsibilities, identifying key pathways for carbon leakage, and promoting the establishment of a fair and effective regional low-carbon transition cooperation mechanism (Santer O K & Bluwstein J, 2025).

Therefore, this paper will utilize the mature analytical framework of multi-regional input-output model to conduct consumption-side accounting of carbon emissions in major "Belt and Road" countries. Specifically, this study aims to achieve the following objectives:

1. **Role Identification:** By quantifying net carbon transfers, this study delineates the "producer" or "consumer" roles of nations within the carbon flow network, thereby exposing structural imbalances in responsibility allocation.

2. **Network Deconstruction:** Tracing the transnational origins of carbon footprints, analyzing the interdependence between core and peripheral countries, and revealing the "center-periphery" structure of carbon flow networks.

3. Root Cause Analysis: By deconstructing the industrial sources of carbon emissions in key countries, this study links macro-level flow patterns with micro-level economic structures to elucidate carbon lock-in risks across different development models.

4. Policy discussion: Based on the above findings, explore the construction of a fair and effective "Belt and Road" regional low-carbon transition cooperation path.

2 Literature Review

To achieve the aforementioned research objectives, the core methodology employed in this paper is the environment-expanding multi-regional input-output model. This section will conduct a literature review from three aspects: the evolution of carbon accounting methods, the application of MRIO models, and carbon leakage research.

2.1 Carbon Accounting Methodology: From Production to Consumption

Wang Yong et al. (2025) proposed that climate change accounting, based on international standards such as SEEA2012, SEEA2014, and SEEA2021, has become the statistical foundation for global nations to address climate change. Its in-depth implementation has significantly improved environmental-economic accounting systems and enhanced climate change response capabilities. Traditional carbon emission accounting follows the production-side principle under the United Nations Framework Convention on Climate Change (UNFCCC), only tracking direct emissions occurring within a country's territory. While this method facilitates monitoring and management, it has notable limitations in the context of deepening global division of labor: it may underestimate emissions from developed countries consuming high-carbon products while overestimating emissions from developing countries that bear the role of "world factories." To more fairly allocate emission responsibilities, the academic community has proposed the consumption-side accounting principle, which calculates the total global carbon emissions caused by meeting a country's final consumption demand—its "carbon footprint." Consumption-side accounting requires tracking all emissions throughout a product's global supply chain, with its methodological foundation being input-output analysis.

2.2 Application and Development of Input-Output Model in Carbon Accounting

The input-output model was proposed by Leontief, providing a foundational framework for systematically describing the complex interdependencies among various sectors within an economic system. To further track the environmental footprint of economic activities, the academic community has integrated environmental data such as carbon emissions, leading to the development of an environmental extension of the input-output model. Building on this, to accurately characterize the implicit carbon emissions in international trade, the multi-regional input-output model emerged. By consolidating input-output tables from different countries or regions, this model can clearly reveal the

environmental burdens carried by products and services in cross-border flows. As Subhasinghe et al. (2024) pointed out, extending traditional economic models with multi-regional input-output matrices can effectively capture the complex economic and environmental interactions on a global scale. This approach also provides a powerful tool for analyzing the carbon emission impacts of regional cooperation initiatives such as the Belt and Road. For example, Pan Chen et al. (2022) noted through correlation analysis that, driven by the "dual carbon" goals, the low-carbon transformation of the energy structure and the optimization of industrial structures will significantly impact the suppression of carbon emission growth, and the multi-regional input-output model is a crucial pathway for identifying and quantifying these structural effects.

Early global MRIO databases, such as GTAP, WIOD, and EORA, provided a foundational framework for transnational environmental research, giving rise to numerous pioneering studies on trade-related embodied carbon. In recent years, with the improvement in data availability and computational power, research has become more refined. This study focuses on regions along the "Belt and Road", particularly paying attention to the detailed carbon flows between China and countries along the route. To more accurately depict the complex supply chains and high-resolution sectoral data in this region (Hua Ruixiang and Jing Yiran, 2025), this study employs the China Emissions Database (CEADs). This database not only covers major countries along the route but also provides a higher-resolution sectoral characterization of China and its trading partners. Its accounting system is closely aligned with official statistics, making it more suitable for supporting the structural and mechanistic in-depth analysis of the "Belt and Road" carbon network.

This study employs the MRIO model's standard computational workflow: first calculating the direct consumption coefficient matrix (A), then deriving the Leontief inverse matrix (L), and finally integrating the direct emission intensity diagonal matrix to derive the carbon emission matrix driven by final demand. This methodology enables precise decomposition of country-sector-specific emissions driven by final demand into global production sectors.

2.3 "Belt and Road" and Carbon Leakage Research

Carbon leakage refers to the phenomenon where carbon emissions shift from countries with strict climate policies to those with lax policies due to varying levels of climate policy intensity, which may undermine the overall effectiveness of global emission reduction efforts (Kittel L& Fahl U, 2025). The significant differences in development levels, industrial structures, and climate policies among Belt and Road countries make them potential high-risk areas for carbon leakage. Although existing research has focused on bilateral trade-related carbon flows between China and Belt and Road countries, most studies are limited to a single-country perspective and lack systematic examination from a regional network perspective. Particularly, there remains insufficient analysis of sectoral pathways, key hubs, and their dynamic evolution in carbon flows.

At the governance level, the fundamental resolution of carbon leakage is considered key to achieving the goals of the Paris Agreement (Liu Yajun and Wang Tongqin, 2024).

The current governance model centered on carbon pricing still faces limitations in practice, potentially increasing the burden on developing countries and affecting their policy autonomy. Therefore, it is particularly necessary to promote more inclusive and effective international cooperation mechanisms. Meanwhile, recent research has begun to focus on the green effects of the Belt and Road Initiative itself. Analysis shows that through multi-regional input-output models with environmental expansion, jointly building the Belt and Road can help reduce regional carbon leakage intensity, and its green technology spillovers and optimization of value chain division of labor have positive emission reduction impacts (Huang Xiaowu et al., 2024). This provides a basis for further identifying and leveraging the green synergistic potential of the initiative.

2.4 Focus on the Investment Effects of "Belt and Road" to Address Both Environmental and Economic Issues

With the deepening of the Belt and Road Initiative, China's investment in countries along the route has become a key factor driving regional economic development and the evolution of carbon patterns. In recent years, the academic community has paid increasing attention to the dual economic and environmental effects of such investments, particularly focusing on the potential issues of carbon emission shifts and structural lock-in that may arise while promoting economic growth.

Chai Jingxuan (2022) proposed that the growth of China's outward direct investment has had a positive impact on the economic development of countries along the "Belt and Road", but it has also brought challenges of carbon emission transfer, making the global carbon reduction task more arduous, thereby emphasizing the necessity of optimizing the investment structure and promoting green technologies. Zhang Jinzhu et al. (2021) pointed out that energy investment has a significant driving effect on the economic growth of countries along the "Belt and Road", but it has also led to an increase in carbon emissions, resulting in significant regional heterogeneity in the cost-benefit of economy and environment, thus providing an important reference for the green and low-carbon transformation of China's energy investment structure.

In view of this, based on existing literature, this study employs a multi-regional input-output model to construct a "Belt and Road" regional carbon emission flow network, aiming to systematically reveal the channels, scale, and structural characteristics of carbon leakage within and beyond the region. The specific analysis will rely on bilateral implicit carbon flow matrices between countries and sectoral data: first, by calculating net carbon transfers to define the roles of countries in global carbon division of labor; second, by deconstructing the transnational sources of consumption-side emissions from typical countries to reveal network dependency structures; finally, by aggregating industrial sectors to analyze the industrial structure roots of carbon emissions, thereby providing new empirical evidence and analytical dimensions for understanding the complex mechanisms of carbon flows in the "Belt and Road" region.

3 Methodology

This study employs an environment-expanding multi-regional input-output model as its core analytical framework. The MRIO model systematically tracks all economic activities generated by final demand within global production networks (Abbood K & Meszaros F, 2023) and accurately quantifies corresponding carbon emissions, serving as a leading tool for consumption-side carbon accounting and analysis of implicit carbon flows.

3.1 Data Sources

The core data of this study comes from the global multi-regional input-output tables and environmental accounts released by the China Emissions Database (CEADs). This database covers more than 180 countries (regions) worldwide, including the vast majority of "Belt and Road" countries of interest in this paper, and decomposes the economic system into 133 subsectors, providing a highly refined analytical foundation. The data mainly includes:

1. Multi-region input-output table: contains intermediate inputs (Z matrix) of various countries and sectors, final demand (F matrix, including household consumption, government consumption, capital formation, etc.) and total output (X vector) data.
2. Departmental carbon dioxide emission accounts: Provide direct CO₂ emissions (CO₂vectors) from production sectors across countries and departments.

3.2 Model Construction and Calculation Steps

The model is built and calculated in MATLAB environment, the core steps are as follows.

1. Calculate direct carbon emission intensity. First, determine the direct carbon emission intensity per country-sector combination, i.e., the amount of direct carbon emissions per unit of output.

$$CO2_Inventory_j = \sum_{i=1}^m CO2_{i,j} \quad (1)$$

Where, $CO2_{i,j}$ represents the CO₂ emissions of the j-th country/sector; m is the number of departments, and j is the country/sector index (245 countries in total).

$$CO2_Inventory_j = \frac{CO2_Inventory_j}{X_j} \quad (2)$$

Where, X_j Total output for country/sector j.

2. Construct the direct consumption coefficient matrix. Based on the intermediate input matrix Z and total output vector X, calculate the global-level direct consumption coefficient matrix A.

$$A = \frac{Z}{X^T} \quad (3)$$

Where, Z is the intermediate input matrix. X is the total output vector.

3. Calculate the Leontief inverse matrix. The Leontief inverse matrix L reflects the complete relationship between final demand and total output, encompassing all indirect input demands across the production chain.

$$L=(I-A)^{-1} \quad (4)$$

4. Accounting for consumption-side carbon footprint and implied carbon flows. By diagonalizing direct carbon emission intensity into a matrix and multiplying it with the Leontief inverse matrix L and final demand matrix F , a detailed implied carbon flow matrix can be derived. The matrix's rows represent country-sectors where production occurs, while its columns indicate country-demand categories that generate this production, with elements representing emission volumes.

The diagonalized CO_2 intensity matrix is:

$$CO_2_Intensity=diag(CO_2_Intensity) \quad (5)$$

5. Data Aggregation. To facilitate analysis, the department-level flow matrix (dimensions: number of countries $\times$ 133 departments $\times$ number of countries $\times$ demand categories) is aggregated in two steps. First, the production side is aggregated by country to obtain a country-level implicit carbon output matrix. Second, the final demand side is simplified to the country level (by merging different demand categories) to generate the final bilateral implicit carbon flow matrix between countries (dimensions: producing country $\times$ consuming country).

Carbon footprint (sectoral level):

$$Carbon_footprint=CO_2_Intensity \times L \times f \quad (6)$$

Where, f As the final demand vector.

Carbon footprint by country (first-level aggregation):

$$Carbon_footprint_n(i,:)=\sum_{k=1}^{133} Carbon_footprint((i-1) \cdot 133+k,:) \quad (7)$$

$$i=1,2,\dots,245$$

Summarize by country and final demand type (second-level summary):

$$Carbon_footprint_n1(:,i)=\sum_{t=1}^3 Carbon_footprint_n(:,(i-1) \cdot 3+t) \quad (8)$$

Summarize carbon footprint by sector and country (for sector analysis):

$$Carbon_footprint_n2(:,i)=\sum_{t=1}^3 Carbon_footprint(:,(i-1) \cdot 3+t) \quad (9)$$

Department mapping to major classes (using bridge matrix):

$$Carbon_footprint_n3^{(i)}=B^T \times Carbon_footprint_n2^{(i)} \quad (10)$$

B 133×4 as the bridging matrix, with dimensions, and $Carbon_footprint_n2^{(i)}$ the carbon footprint vector of 133 sectors corresponding to the country.

4 Results and Analysis

Based on the multi-regional input-output model (MRIO) and the CEADs database, this study conducted precise accounting of carbon flow patterns in 49 core Belt and Road countries. The data analysis follows the following logic: first, defining their roles based on the difference between production-side and consumption-side emissions; second, conducting in-depth analysis of extreme cases; and finally, revealing structural characteristics from a regional perspective.

4.1 Definition of Belt and Road countries: Structural Imbalance Between Production and Consumption Side Emissions

We first calculated the carbon emissions from both production and consumption sides across global countries, as shown in Figure 1. The supply-side and consumption-side correlations should generally follow a positive proportional diagonal distribution.

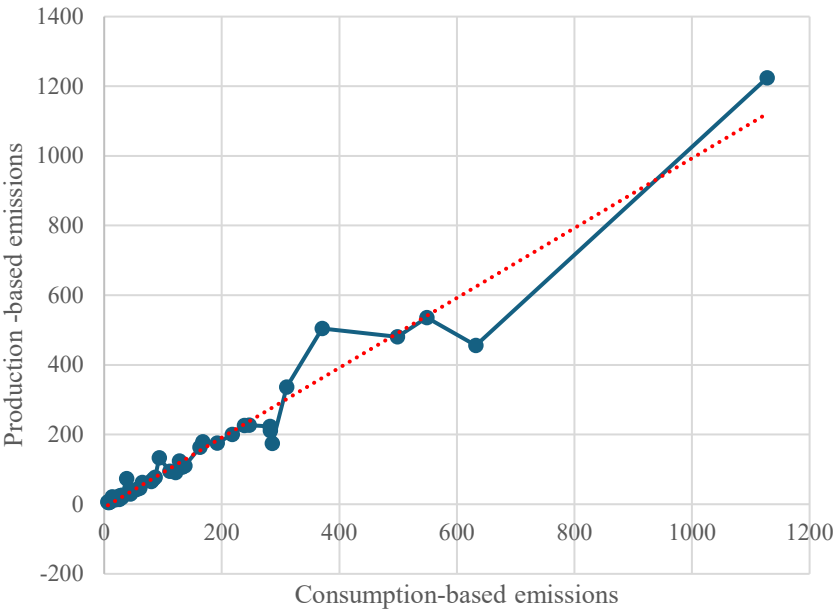


Fig. 1. Dual Perspectives of Carbon Emission Accounting: A Comparative Diagram of Production and Consumption Sides

Through further research on the structural differentiation of carbon emission responsibility allocation among Belt and Road countries, the distribution map of consumption side/production side countries in Figure 2-3 reveals that China, India, and Russia, as major players on both the consumption and production sides, occupy an absolute high position in the horizontal comparison with Belt and Road countries in terms of absolute values, while countries in Central Asia, the Middle East, and Africa are relatively low.

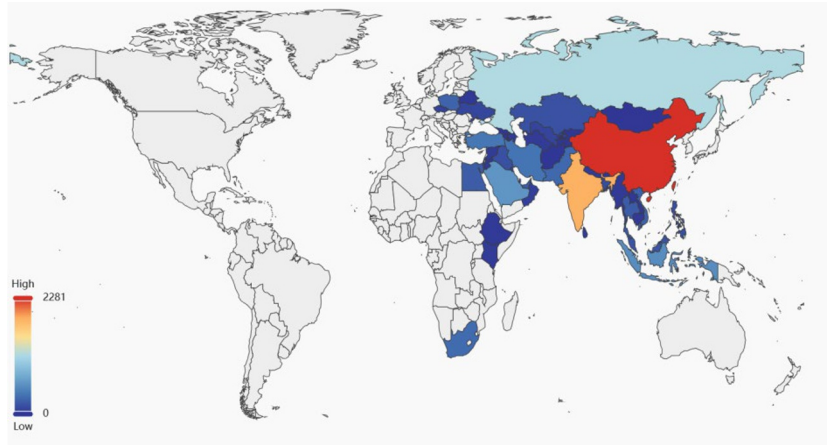


Fig. 2. "Belt and Road" countries along the consumption side carbon emissions geographical distribution map

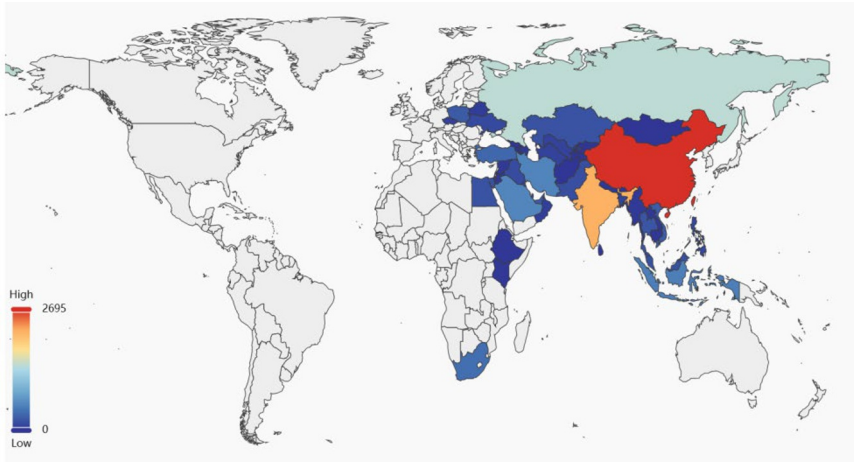


Fig. 3. "Belt and Road" countries production side carbon emissions geographical distribution map

4.2 Absolute Data Analysis: The Role of the State

4.2.1 China's Core Producer Status.

Data shows that China is not only the largest producer ($PBE = 8650.88 \text{ Mt CO}_2$), but also the country with the largest absolute value of net transfer (-424.96 Mt CO_2). This annual carbon net export of up to 425 million tons means that China has taken on an additional carbon emission responsibility equivalent to 93% of Germany's annual production emissions to meet global consumption demands. This pattern of carbon flow is closely linked to China's large-scale investment layout, capacity cooperation, and the

resulting global value chain division within the region. This quantitative outcome confirms China's core hub status in the "Belt and Road" carbon flow network.

4.2.2 The Extreme Consumer Role of Germany.

Germany exhibits the typical characteristics of "high consumption, low production", with its net carbon transfer amount reaching 176.09 Mt CO₂, accounting for 28% of its consumption-side emissions. This means that nearly one-third of Germany's consumption-related carbon emissions actually occur outside its borders, primarily transferred through supply chains to producing countries including China.

4.2.3 Carbon Divergence Among Developing Nations.

Pakistan (PAK, +111.77 Mt CO₂) and Indonesia (IDN, +18.42 Mt CO₂), both developing countries, demonstrate contrasting trends in carbon transfers. Pakistan, as a net consumer, indicates that its rapidly growing consumption demand has outpaced its production capacity. In contrast, Indonesia, while also a net consumer, exhibits a relatively smaller net transfer volume, reflecting a more balanced production-consumption dynamic.

4.3 Structural Deconstruction of Carbon Flow Network: Analysis of Supply Chain Dependence and Initiative Effect in Developing Countries

To thoroughly analyze the actual impact of the Belt and Road Initiative on the carbon emission structure of developing countries along the route, this section focuses on three representative cases: Indonesia (IDN), Pakistan (PAK), and Brunei (BRN). By deconstructing the transnational sources of their consumption-side carbon emissions, it analyzes their specific patterns of embedding in the global carbon flow network and preliminarily assesses the substantial impacts they gain from connectivity. The structural decomposition results are reported in Table 1.

Table 1. Structural decomposition of carbon emission sources on the consumption side of typical developing countries along the Belt and Road (unit: contribution, million tons of CO₂; proportion)

Consumption (Role)	Country	Top 3 main countries of origin	Contribution amount	Consumption share of total emissions
Pakistan (PAK)		1. Pakistan (self)	171.07	59.79%
		2. Iran (IRN)	86.07	30.08%
		3. China (CHN)	20.84	7.28%
Indonesia (IDN)		1. Indonesia (self)	420.50	84.28%
		2. China (CHN)	51.39	10.30%
		3. Singapore (SGP)	5.52	1.11%
Brunei (BRN)		1. Brunei (self)	10.60	87.75%
		2. Malaysia (MYS)	0.27	2.20%
		3. China (CHN)	0.58	4.77%

Data shows that the dependence structure of carbon emissions from consumption in the three countries exhibits significant differences, reflecting their distinct economic development stages, resource endowments, and external economic ties. Indonesia demonstrates the characteristic of "high internal circulation," with over 84% of consumption emissions met by its own production, which corroborates its role as a "weak net consumer" in Section 4.1. Its external carbon sources mainly come from China (10.30%) and the regional hub Singapore, indicating that its development primarily relies on the domestic market while also accessing the global manufacturing network through the Belt and Road initiative with limited but deep connections.

In contrast, Pakistan's dependency structure reveals a "geographically concentrated reliance under internal and external imbalances." Although its own production meets nearly 60% of consumption emissions, its dependence on external carbon sources is highly concentrated on neighboring Iran (30.08%), followed by the global manufacturing hub China (7.28%). This highlights the profound impact of its energy consumption structure and specific regional trade ties, and also suggests that its economic development and carbon footprint growth are strongly constrained by geopolitical factors.

As a typical resource-exporting economy, Brunei's "resource-subsistence" structure is characterized by nearly 88% of consumption emissions originating domestically. However, approximately 5% of consumption carbon footprints are imported through supply chains in Malaysia and China, indicating that even in highly self-sufficient economies, the trade interconnectivity facilitated by the Belt and Road has reshaped the geographical sources of consumption carbon emissions to a subtle yet critical extent.

The cases of the three countries collectively demonstrate that the carbon linkage intensity between developing countries along the Belt and Road and China is closely related to their economic structures. This structure not only reflects economic connections but also constitutes potential channels for "carbon leakage." The nature of investment projects (e.g., whether they are low-carbon), location selection, and their relevance to local industries directly influence the direction and intensity of carbon leakage. For example, investments in Pakistan's energy sector may affect its dependence on external energy sources (Iran), while manufacturing investments in Indonesia directly increase its supply chain's carbon linkage with China.

The "Belt and Road" initiative advocates "connectivity," which is essentially a reshaping of channels, providing developing countries with the possibility to reduce excessive dependence on a single market or supply chain (Yu Bowen, 2025). Within this carbon flow network jointly constructed by investment and trade, by participating in capacity cooperation and green technology transfer under the initiative, developing countries have the opportunity to enhance the added value and low-carbon level of their local manufacturing industries, thereby internalizing part of the consumption carbon footprint and reducing the overall carbon intensity of supply chains. This implies that the ultimate carbon impact of the initiative will profoundly depend on whether specific investment projects continue or transform the traditional industrial division of labor model.

4.4 Deconstruction of Industrial Carbon Emission Structure: Carbon Imprint of Development Model and Lock-in Risk

To explore the economic drivers behind the role of national carbon emissions, this section deconstructs the economic system into four major industrial categories: agriculture, manufacturing, energy industry, and services. We focus on the "4+1" typical country combination, analyzing the industrial sources of production-side carbon emissions (Table 2), aiming to reveal how the diversified economic development models of "Belt and Road" countries have left a profound imprint on their carbon emission structures, thereby giving rise to distinct challenges in low-carbon transition.

Table 2. Industrial Composition and Role Analysis of Carbon Emissions from Production Sides in Typical Countries (Unit: Million Tons of CO₂)

Country (role)	Agriculture	Manufactory	Energy	Service
China (CHN)	139.80	1773.83	5811.68	925.58
core net producer	(1.62%)	(20.50%)	(67.18%)	(10.70%)
Germany (DEU)	12.72	36.59	224.26	182.30
primary net consumer	(2.79%)	(8.03%)	(49.19%)	(39.99%)
Pakistan (PAK)	0.37	32.96	79.88	61.16
high growth net consumer	(0.21%)	(18.90%)	(45.81%)	(35.08%)
Vietnam (VNM)	9.40	62.19	123.63	30.93
emerging net producer	(4.16%)	(27.50%)	(54.67%)	(13.68%)
Zambia (ZMB)	0.12	1.13	2.61	2.69
edge depth dependent	(1.78%)	(17.26%)	(39.86%)	(41.09%)

4.4.1 The Empirical Closed Loop from "Role" to "Structure".

The "high-carbon productivity" characteristics of net producers (CHN, VNM) are significant. Data shows that China and Vietnam, as major producers, have carbon emission structures dominated by energy and manufacturing. China's energy sector accounts for 67.18% of carbon emissions, while manufacturing accounts for 20.50%, totaling over 87%; Vietnam's energy and manufacturing sectors account for 54.67% and 27.50% respectively, totaling over 82%. This structurally confirms their roles as "carbon base-ments" in the global manufacturing supply chain.

Net consumers (DEU, PAK) exhibit distinct structural variations. Germany, as a highly industrialized consumer nation, channels most of its carbon emissions into domestic energy (49.19%) and services (39.99%), with manufacturing contributing merely 8.03%—a pattern reflecting its reliance on supply chains to offshore substantial emissions. In contrast, Pakistan, another net consumer, maintains a more balanced emission structure: energy (45.81%), services (35.08%), and manufacturing (18.90%). This demonstrates that its consumption growth remains strongly dependent on domestic industrial synergy rather than complete import substitution.

4.4.2 The Industrial Roots and Lock-in Effect of Carbon Dependence.

Zambia's case highlights the carbon emission characteristics of resource-dependent economies. Energy and services account for 39.86% and 41.09% of total emissions respectively, while manufacturing contributes only 17.26% and agriculture a negligible 1.78%. This structure reveals the economy's heavy reliance on resource extraction and related services, coupled with a weak manufacturing base. As a result, Zambia must export resource products to import manufactured goods, creating a "resource-trade" dual dependence that balances carbon emissions with economic gains.

As a rapidly industrialized nation, Vietnam's carbon emission structure shows energy sources account for 54.67% and manufacturing for 27.50%, demonstrating the strong correlation between economic growth and energy consumption as well as industrial production. Without advancing clean energy transition and low-carbon manufacturing upgrades, the country's further development will face rigid constraints of 'growth-carbon emissions' and develop path dependence.

4.4.3 Implicit "Carbon Responsibility Transfer" and Global Division of Labor.

The comparison of carbon emission structures between China and Germany clearly reveals the mechanism of carbon responsibility transfer under global industrial division of labor. China's manufacturing and energy sectors account for a combined carbon emission share of 87.68%, while Germany's corresponding proportion is only 57.22%, with its service sector contributing nearly 40% of carbon emissions. Combined with the previous conclusion that a significant portion of Germany's consumption-side carbon emissions originates from China, it is evident that Germany transfers part of its carbon emission responsibility to China through imports, with the latter effectively bearing the production emissions for global consumption. This quantifies, at the industrial level, the misalignment between the "producer responsibility" and "consumer responsibility" systems, highlighting the rationality of consumption-side accounting in the global distribution of climate responsibilities.

The industrial structure of carbon emissions in various countries reflects their development stages, resource endowments, and roles in international division of labor: China, as the "world factory," bears high-intensity production emissions; Germany achieves domestic low-carbonization through its service sector and energy system, but transfers emissions via trade; Vietnam continues to follow the traditional high-carbon path of industrialization; Zambia, on the other hand, is trapped in a structural dependence on resource exports and imported manufactured goods. This diversified pattern indicates that the low-carbon transition of Belt and Road countries cannot be achieved through a single model, but must involve designing differentiated decarbonization pathways and regional coordination mechanisms tailored to their industrial realities.

5 Research Conclusions and Discussion

This study systematically calculated and deeply deconstructed carbon flows in 49 core Belt and Road countries through an environmental expansion multi-regional input-output model (MRIO). The research not only quantified the scale and direction of carbon

flows but also revealed, through data, the hidden pattern of carbon emission responsibility allocation, structural dependency relationships, and development path lock-in effects behind global trade. It provides a key empirical foundation for scientifically evaluating the environmental effects of China's investments in these countries and the resulting "carbon leakage" issues.

5.1 Main Conclusions

First, the "Belt and Road" regional carbon flows exhibit a dual "core-periphery" pattern composed of "responsibility mismatch" and "dependence structure," which is highly isomorphic to China's investment and trade network within the region. As a core net producer, China bears an annual net export of implicit carbon equivalent to 424.96 million tons of CO₂, while major net consumers like Germany transfer 28% of their consumption-side carbon footprint overseas, quantifying the significant responsibility mismatch caused by production-side accounting. In terms of dependency, a "hub-and-spoke structure" centered on China and Germany has formed, along with "unidirectional deep dependence" from numerous developing countries on core producers or regional powers (e.g., Pakistan's dependence on Iran accounts for as high as 30.08%). This confirms the pivotal role of China's investment and trade activities in shaping the regional carbon flow network and delineates the specific pathways of carbon leakage.

Second, the national carbon role is deeply rooted in its heterogeneous industrial development model and faces differentiated "carbon lock-in" risks, which are closely related to the types and sectors of foreign investment. China's carbon emissions are tightly bound to the energy-industry complex (accounting for about 80%), which serves as the carbon base for its status as the "world factory" and corresponding capital exports. Vietnam, as an emerging producer, relies heavily on an energy system that serves export-oriented manufacturing (accounting for 65.8%), posing a rigid "growth-carbon" binding risk, which is closely linked to receiving export-oriented manufacturing investments. Zambia, on the other hand, is locked into a single structure of "high-carbon resource exports" (energy industry accounting for 79.5%), reflecting how resource extraction investments may exacerbate economic and environmental homogeneity. Although Germany's domestic industrial structure has become low-carbon, its massive "carbon outsourcing" reveals the geographical transfer impact of consumption-side investments (such as through supply chain management) on global emissions.

Third, the current carbon flow pattern is essentially a spatiotemporal mismatch between the "right to development" and "emission reduction responsibility" under globalized division of labor, which has been solidified and manifested due to large-scale international investments. The territorial-based production-side accounting system has burdened countries that have undertaken a large amount of China's manufacturing and infrastructure investments with excessive explicit carbon responsibilities, while those that enjoy final consumption benefits have underestimated their implicit carbon impacts. This pattern, shaped by long-term international investments, industrial transfers, and trade agreements, may render any unilateral climate policy ineffective due to carbon leakage, or even exacerbate inequity, unless coordinated governance is implemented from the sources of investment and consumption-side responsibilities.

5.2 Discussion: Towards a Low-carbon Transition for Equity

The findings of this study provide profound insights for optimizing China investment and promoting the green and low-carbon coordinated development of the Belt and Road.

First, it is essential to promote the establishment of a shared responsibility principle based on the linkage between the consumption side and the investment side. Within the framework of the Belt and Road cooperation, efforts should be made to explore the development of accounting and disclosure guidelines covering the carbon footprint of investments, jointly incentivizing Chinese investors and host countries to avoid high-carbon lock-in from the project planning stage and create a fair competitive environment for green investments. This is the institutional foundation for managing carbon leakage at the source and ensuring the positive effects of the investment environment.

Secondly, the low-carbon transition path must be precisely coupled with investment strategies and the host country's industrial structure, implementing differentiated strategies. For China, it is necessary to promote the transformation of outbound investment from traditional infrastructure to green infrastructure, and from single project contracting to the export of green technology, standards, and management systems. For emerging producers such as Vietnam, investments should focus on the construction of green supply chains and renewable energy support; for resource-rich countries like Zambia, investments should facilitate economic diversification and green resource development; for consumer countries such as Germany, they should be encouraged to jointly invest in third-party low-carbon projects through green procurement and cooperation with China. This requires the financing and investment mechanisms of the "Belt and Road" to be highly targeted and directional.

Finally, China's dual role determines that its transformation direction is key to regional synergistic effects. China is not only a key node in the carbon leakage network but also a major supplier of green technology. Therefore, promoting China's transition from a "carbon transfer hub" to a "green investment and technology diffusion hub" should be the core of the "Green Silk Road" initiative. This requires fully integrating carbon neutrality goals into foreign investment and cooperation policies, and through concrete measures such as establishing the "Belt and Road" Green Investment Fund, promoting ESG (Environmental, Social, and Governance) investment standards, and jointly building low-carbon demonstration zones, making investment a synergistic engine for improving the host country's environment, social inclusion, and economic growth, rather than a channel for carbon leakage.

5.3 Research Perspectives

Future research can be deepened in the following directions: First, conduct long-term dynamic analysis to track the long-term impacts of major China investment projects (such as industrial parks and energy projects) on the carbon flow networks of host countries and regions (Li Hui et al., 2020), and assess the dynamic evolution of their environmental effects. Second, expand the analysis from carbon dioxide to multiple dimensions such as air pollutants, water resource consumption, and job creation, and conduct

a comprehensive evaluation of the synergistic effects of environment, society, and economy to fully measure the net benefits of investments. Third, combine scenarios such as the Belt and Road investment and financing policy reforms and the Carbon Border Adjustment Mechanism (CBAM) to simulate the differential impacts of different policy combinations on investment flows, carbon leakage patterns, and the synergistic benefits of countries, providing accurate pre-enactment for decision-making.

In summary, promoting the low-carbon development of the Belt and Road is not merely about technology transfer, but rather about guiding a profound transformation through responsible investment, which involves the restructuring of global division of labor, rebalancing of development rights, and innovation in international governance, aiming to achieve a win-win situation of environmental integrity, social equity, and economic prosperity. This study aims to provide a data-driven rational footnote and decision-making reference for understanding and shaping the synergistic effects of China's investment in the Belt and Road through scientific accounting and in-depth deconstruction.

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