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Reevaluation of the carbon emissions embodied in global value chains based on an inter-country input-output model with multinational enterprises

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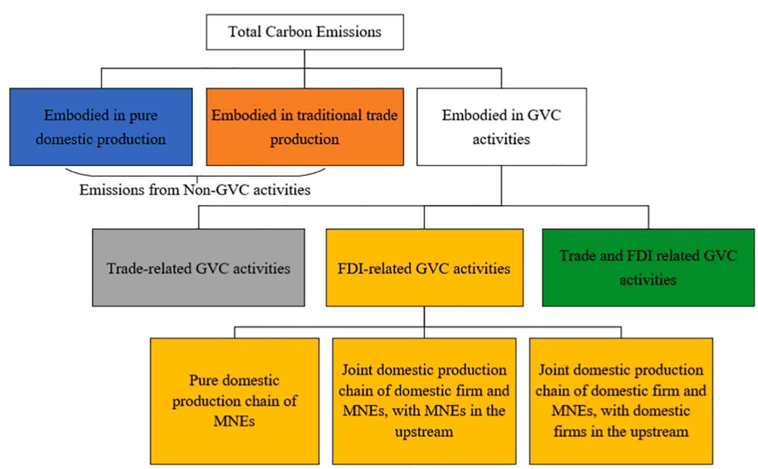
HIGHLIGHTS

- Construct a new decomposition framework distinguishing heterogeneous enterprises.
- The carbon emissions from different activities under two frameworks are evaluated.
- Define "emissions embodied in foreign direct investment (FDI-related GVC emissions)".
- The structure of FDI-related GVC emissions is analyzed.
- Driving factors of the changes in FDI-related GVC emissions are given.

GRAPHICAL ABSTRACT



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ABSTRACT

Multinational enterprises actively participate in global production networks. However, the current global value chain accounting framework fails to consider the emissions originating from the production activities of multinational enterprises in the host country and may underestimate the carbon emissions embodied in global value chain activities. This paper proposed an Inter-Country Input-Output decomposition framework that can distinguish domestic firms and multinational enterprises and recalculated global value chain emissions including emissions embodied in international trade (trade-related GVC emissions), foreign direct investment (FDI-related GVC emissions), and both (trade and FDI related GVC emissions). We found that 1) the carbon emissions originating from global value chain activities were underestimated by about 13.8 percentage points under the original framework in 2016, and a large part was classified as emissions stemming from pure domestic production activities; 2) the FDI-related GVC emissions were notable in high-income economies and high-tech

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manufacturing sectors; 3) foreign direct investment mainly drove the emissions of upstream domestic firms through the joint domestic production linkage between domestic firms and multinational enterprises, especially in upper-middle-income countries; 4) from 2005 to 2016, the FDI-related GVC emissions increased by approximately 704.6 million tons, which was mainly attributed to the scale effect, whereas the carbon intensity effect caused a reduction. The results of this study exhibit a potential significance for the correct identification of the environmental impacts of global production fragmentation, and support policy decisions on national emission responsibilities and quotas determination, differentiated foreign investment decisions, and cleaner production development.

1. Introduction

With the acceleration of globalization, the division of labor and cooperation among various countries has been increasingly optimized, thereby forming global value chain (GVC) networks characterized by trade in intermediate goods. The fragmentation of production and changes in trade patterns highlight the importance of research on global value chains. Countries gain value by participating in GVC activities and generate high emissions at the same time. Therefore, it is very important to accurately identify and trace GVC activities, so that we can clarify the position and the degree of participation of each economy in the global value chains, as well as its role in the economic and environmental fields. However, GVC activities are not limited to international trade, and the cross-border capital [1,2] and knowledge flows [3] of enterprises are regarded as GVC activities.

Within this context, some enterprises have begun to control and manage production establishments (plants) located in multiple countries to maximize profits, which are defined as multinational enterprises (MNEs) [4]. As major participants in GVC activities, MNEs and their foreign affiliates occupy an important position in global carbon emissions. Because of the fragmentation of production and the rise of offshore outsourcing, nearly 80% of global trade [5] and 20% of the total global carbon emissions stemmed from the production activities of MNEs and their suppliers in 2016 [6]. Most current national accounting rules treat all MNEs and domestic firms within the national boundaries as one unit. However, the way that MNEs participate in global value chains are different from that of domestic firms [7]. **On the one hand**, MNEs are the main carriers of international trade, which exerts an important impact on greenhouse gas emissions at the global and national levels [8]. Research has revealed that the emissions embodied in trade are closely related to the position of a single economy in the GVCs [9]. **On the other hand**, MNEs enter the host country market through foreign direct investment (FDI), mainly by building factories or holding shares [10]. The production activities of MNEs in a given host country involve local factors such as labor, resources and environment, as well as foreign factors such as capital, technology and management. Such transnational cooperation production activities are considered as part of GVC activities. MNEs allocate different tasks of their products to countries with different factor endowments in the form of direct investment [11,12], which affects the carbon emissions of the host country on both the production and consumption sides [13]. This part of emissions can be regarded as “FDI-related GVC emissions”. An increase in FDI may lead to an increase in CO_2 emissions per capita [14], but the rise of anti-globalization and the reflow of MNEs may lead to the pollution haven phenomenon, temporarily curbing the increasing trend of global CO_2 emissions in the near future [15]. Zhang et al. [6] and Ortiz et al. [16] found that the carbon transfer caused by the investment of MNEs makes the originating countries bear too little responsibility of carbon emission reduction. The FDI of the developed countries, which act as the main investment home countries, has led to a large transfer of energy-intensive tasks. As a result, the actual carbon emissions of developed countries are underestimated [17,18]. And the migration of energy-intensive industries could actually lead to higher global emissions [19]. Therefore, it is important to pay attention to the role and impact of FDI of multinational enterprises when tracing carbon emissions from the perspective of GVCs.

However, most of the current macro-level GVC emission accounting research mainly focuses on international trade [20,21]. Measuring carbon emissions embodied in international trade has always been an active area. Researchers often use the input–output analysis framework to study the energy-related CO_2 emissions in international trade from the global [22], national [23,24], regional [25,26] and sectoral levels [27,28]. These studies are carried out from the perspective of the value added to accurately reflect the role of countries in the global value chains [29,30,31], and consider the activities where factor content crosses a national border at least once and is used in production outside the home country as GVC activities [32]. Only a few articles measured the investment-related emissions in GVCs based on input–output relationship. López et al. [18] calculated the carbon footprints of MNEs by multiplying the emission intensity coefficient matrix with the final demand matrix and an index that measures the proportion of MNEs in each economy. Zhang et al. [6] used the hypothetical extraction method to trace the carbon transfer embodied in global FDI. Duan and Jiang [15] simulated the global carbon emissions under the scenario of the reflow of MNEs based on an inter-country input–output model distinguishing firm ownership.

Although there are some existing literatures on the environmental effects of MNEs based on multi-regional input–output (MRIO) models, it has not formed a consistent accounting framework. The current accounting framework ignores the role of MNEs and treats them as a whole with local firms. In fact, the affiliates of MNEs and local firms are systematically different in their participation in the global value chains. If affiliates of MNEs participate in global value chains to a higher degree, the existing methods may greatly underestimate the overall level of GVC emissions. Moreover, the existing studies only consider the carbon emissions embodied in trade but not the carbon emissions embodied in FDI when calculating the emissions stemming from GVC activities, resulting in an underestimation of the degree of participation in global value chains of a specific country. The underestimation may cause misjudgment of the relationship between GVC activities and environmental problems, which may harm the interests of both the given country and its trading partners. In this paper, we try to fill this gap by identifying the carbon emissions embodied in investment of multinational enterprises and categorizing them into the emissions of GVC activities to establish a new GVC emission accounting framework.

The major contributions of this paper are as follows: First, it proposes a novel decomposition framework that can distinguish domestic firms and multinational enterprises based on the Activities of Multinational Enterprises (AMNE) database, and recomputes the emissions stemming from GVC activities embodied in international trade and FDI. Second, it extends the current GVC accounting framework, which underestimates the carbon emissions embodied in GVC activities, and compares the results with those under the old framework. Third, this paper defines and identifies “FDI-related GVC emissions” from GVC emissions, then further decomposes FDI-related GVC emissions to assess the impact of the inflow of FDI on the emissions of host economies. The FDI-related GVC emissions are the emissions enabled by the investment of MNEs in the host country, which only include emissions embodied in FDI, and do not include emissions embodied both in international trade and FDI. The findings of this study not only have potential significance in

Table 1
Inter-Country Input-Output table of the domestic firms and MNEs.

Output Input			Intermediate Use							Final Use				Total Output
			country 1		country 2		⋯	country G		country1	country 2	⋯	country G	
			D	F	D	F	⋯	D	F					
Intermediate Input	country 1	D	Z_{DD}^{11}	Z_{DF}^{11}	Z_{DD}^{12}	Z_{DF}^{12}	⋯	Z_{DD}^{1G}	Z_{DF}^{1G}	Y_D^{11}	Y_D^{12}	⋯	Y_D^{1G}	X_D^1
		F	Z_{FD}^{11}	Z_{FF}^{11}	Z_{FD}^{12}	Z_{FF}^{12}	⋯	Z_{FD}^{1G}	Z_{FF}^{1G}	Y_F^{11}	Y_F^{12}	⋯	Y_F^{1G}	X_F^1
	country 2	D	Z_{DD}^{21}	Z_{DF}^{21}	Z_{DD}^{22}	Z_{DF}^{22}	⋯	Z_{DD}^{2G}	Z_{DF}^{2G}	Y_D^{21}	Y_D^{22}	⋯	Y_D^{2G}	X_D^2
		F	Z_{FD}^{21}	Z_{FF}^{21}	Z_{FD}^{22}	Z_{FF}^{22}	⋯	Z_{FD}^{2G}	Z_{FF}^{2G}	Y_F^{21}	Y_F^{22}	⋯	Y_F^{2G}	X_F^2
	⋮		⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋱	⋮	⋮
	country G	D	Z_{DD}^{G1}	Z_{DF}^{G1}	Z_{DD}^{G2}	Z_{DF}^{G2}	⋯	Z_{DD}^{GG}	Z_{DF}^{GG}	Y_D^{G1}	Y_D^{G2}	⋯	Y_D^{GG}	X_D^G
		F	Z_{FD}^{G1}	Z_{FF}^{G1}	Z_{FD}^{G2}	Z_{FF}^{G2}	⋯	Z_{FD}^{GG}	Z_{FF}^{GG}	Y_F^{G1}	Y_F^{G2}	⋯	Y_F^{GG}	X_F^G
Value-added			Va_D^1	Va_F^1	Va_D^2	Va_F^2	⋯	Va_D^G	Va_F^G					
Total Input			$X_D^{1'}$	$X_F^{1'}$	$X_D^{2'}$	$X_F^{2'}$	⋯	$X_D^{G'}$	$X_F^{G'}$					
Emissions			E_D^1	E_F^1	E_D^2	E_F^2	⋯	E_D^G	E_F^G					

accurately identifying the environmental impacts of global production fragmentation, but also provide a new perspective for the study of carbon emission responsibilities in different countries. This paper provides useful implications for carbon emissions reduction policies in developing economies such as China and Southeast Asian countries, which are the destinations of high-carbon tasks transfer. These host countries should consider the actual carbon emissions of firms with different ownerships when setting emission limits for targeting firms.

The remainder of the paper is organized as follows: Section 2 introduces the technical methods, including the carbon emissions accounting framework and driving factor decomposition methods considering MNEs. Sections 3 and 4 present the empirical results. Section 3 describes the carbon emissions originating from the different production activities (pure domestic production, traditional trade, and GVC activities) of domestic firms and MNEs at the global, national, and industry levels and analyzes the structure of FDI-related GVC emissions. Section 4 examines the driving factors of the changes in FDI-related GVC emissions during different time periods. Section 5 concludes.

2. Methodology and data

In 2018, the Organisation for Economic Cooperation and Development (OECD) released a new AMNE database to better examine the impact of MNEs on GVC networks [33] and proposed Inter-Country Input-Output Tables (ICIO) that distinguished domestic companies, MNEs and their foreign affiliates. This provides a new way and data support to analyze the role of MNEs in economic, employment and environmental fields [34–36].

According to earlier trade and production activity decomposition research [32,37], we propose a decomposition model for carbon emissions that distinguishes the heterogeneity of enterprises. Table 1 provides the ICIO table according to the firm ownership considering G countries and N industries. The superscript identifies the country, where the former is the supply country, and the latter is the demand country. The subscript denotes the enterprise ownership, where D and F indicate domestic firms and MNEs, respectively. Z (2GN × 2GN) is the intermediate use matrix, Z_{DF}^{ij} (N × N represents the intermediate products produced by domestic firms in country i that are invested in reproduction by MNEs in country j; Y (2GN × G) is the final demand matrix, Y_D^{ij} (N × 1) represents the final products produced by domestic firms in country i used in country j; X (2GN × 1) is the total output vector; E_D (1 × GN) and E_F (1 × GN) are the carbon emissions of domestic firms and MNEs, respectively.

The row equilibrium of the ICIO table of the domestic firms and MNEs is as follows:

$$\begin{bmatrix} Z_{DD}^{11} & Z_{DF}^{11} & \cdots & Z_{DD}^{1G} & Z_{DF}^{1G} \\ Z_{FD}^{11} & Z_{FF}^{11} & \cdots & Z_{FD}^{1G} & Z_{FF}^{1G} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ Z_{DD}^{G1} & Z_{DF}^{G1} & \cdots & Z_{DD}^{GG} & Z_{DF}^{GG} \\ Z_{FD}^{G1} & Z_{FF}^{G1} & \cdots & Z_{FD}^{GG} & Z_{FF}^{GG} \end{bmatrix} \mu + \begin{bmatrix} Y_D^{11} & Y_D^{12} & \cdots & Y_D^{1G} \\ Y_F^{11} & Y_F^{12} & \cdots & Y_F^{1G} \\ \vdots & \vdots & \ddots & \vdots \\ Y_D^{G1} & Y_D^{G2} & \cdots & Y_D^{GG} \\ Y_F^{G1} & Y_F^{G2} & \cdots & Y_F^{GG} \end{bmatrix} \mu = \begin{bmatrix} X_D^1 \\ X_F^1 \\ \vdots \\ X_D^G \\ X_F^G \end{bmatrix} \tag{1}$$

where μ is the unit column vector. The final demand matrix Y comprises Y^L and Y^E, which are the final products and services satisfying the domestic and export demands, respectively. ˆ denotes the diagonalization operation.

$$\widehat{Y}^L = \begin{bmatrix} \widehat{Y}_D^{11} & 0 & \cdots & 0 & 0 \\ 0 & \widehat{Y}_F^{11} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \widehat{Y}_D^{GG} & 0 \\ 0 & 0 & \cdots & 0 & \widehat{Y}_F^{GG} \end{bmatrix}, \widehat{Y}^E = \begin{bmatrix} 0 & 0 & \cdots & \widehat{Y}_D^{1G} & 0 \\ 0 & 0 & \cdots & 0 & \widehat{Y}_F^{1G} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \widehat{Y}_D^{G1} & 0 & \cdots & 0 & 0 \\ 0 & \widehat{Y}_F^{G1} & \cdots & 0 & 0 \end{bmatrix}$$

$A^{ij} = \frac{Z^{ij}}{X^j} (i = 1, 2, \cdots, G, i \neq j)$ represents the direct input coefficient of the intermediate products of economy i in the output of economy j. The intermediate input matrix A is:

$$\begin{bmatrix} A_{DD}^{11} & A_{DF}^{11} & \cdots & A_{DD}^{1G} & A_{DF}^{1G} \\ A_{FD}^{11} & A_{FF}^{11} & \cdots & A_{FD}^{1G} & A_{FF}^{1G} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ A_{DD}^{G1} & A_{DF}^{G1} & \cdots & A_{DD}^{GG} & A_{DF}^{GG} \\ A_{FD}^{G1} & A_{FF}^{G1} & \cdots & A_{FD}^{GG} & A_{FF}^{GG} \end{bmatrix}$$

A^L and A^E are the diagonal sub-matrices and off-diagonal sub-matrices of A (containing D and F), which are the local and foreign direct consumption coefficient matrices, respectively; A^O and A^{OE} are the diagonal sub-matrix of A^L and A^E, which are the local direct consumption coefficient matrices among enterprises of the same and different ownerships within a single economy, respectively.

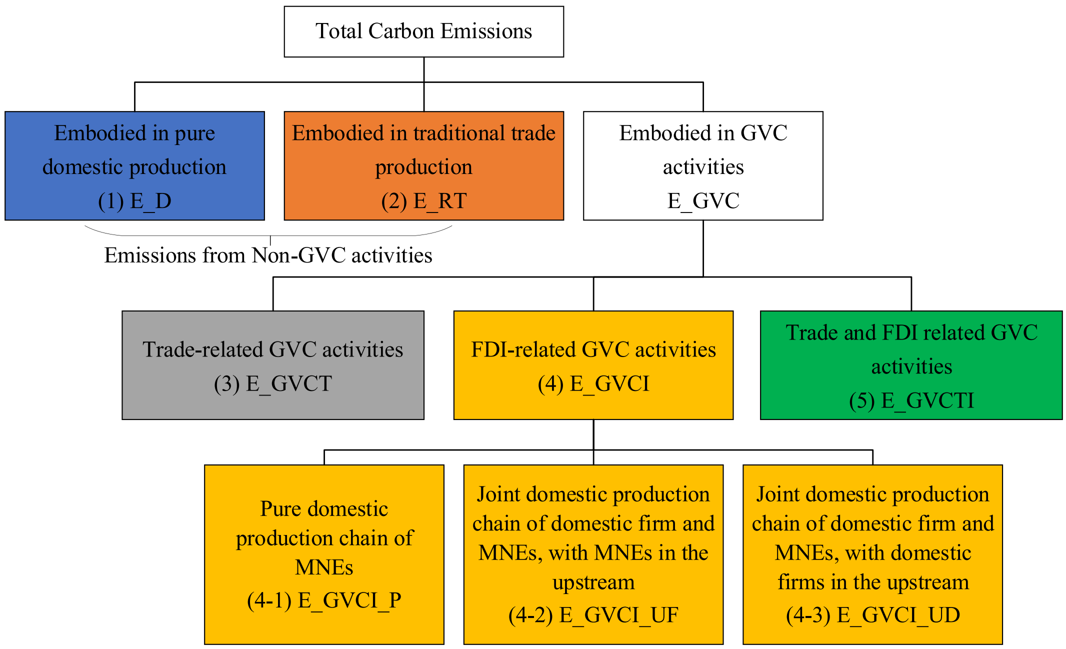

Fig. 1. Accounting framework of the total carbon emissions from the perspective of GVCs.

$$A^L = \begin{bmatrix} A_{DD}^{11} & A_{DF}^{11} & \cdots & 0 & 0 \\ A_{FD}^{11} & A_{FF}^{11} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & A_{DD}^{GG} & A_{DF}^{GG} \\ 0 & 0 & \cdots & A_{FD}^{GG} & A_{FF}^{GG} \end{bmatrix}, A^E = \begin{bmatrix} 0 & 0 & \cdots & A_{DD}^{1G} & A_{DF}^{1G} \\ 0 & 0 & \cdots & A_{FD}^{1G} & A_{FF}^{1G} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ A_{DD}^{G1} & A_{DF}^{G1} & \cdots & 0 & 0 \\ A_{FD}^{G1} & A_{FF}^{G1} & \cdots & 0 & 0 \end{bmatrix}$$

$$A^O = \begin{bmatrix} A_{DD}^{11} & 0 & \cdots & 0 & 0 \\ 0 & A_{FF}^{11} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & A_{DD}^{GG} & 0 \\ 0 & 0 & \cdots & 0 & A_{FF}^{GG} \end{bmatrix}, A^{OE} = \begin{bmatrix} 0 & 0 & \cdots & A_{DD}^{1G} & 0 \\ 0 & 0 & \cdots & 0 & A_{FF}^{1G} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ A_{DD}^{G1} & 0 & \cdots & 0 & 0 \\ 0 & A_{FF}^{G1} & \cdots & 0 & 0 \end{bmatrix}$$

The Leontief inverse matrix $B = (I - A)^{-1}$ represents the complete demand for the output of each department of an economy for each extra unit of final products produced by each department of another economy. $B^O = (I - A^O - A^{OE})^{-1}$ is the global Leontief inverse matrix that only reflects the linkages between domestic firms and MNEs. $L = (I - A^L)^{-1}$ is the local Leontief inverse matrix, and $L^O = (I - A^O)^{-1}$ is the local Leontief inverse matrix that only reflects the linkages among firms with the same ownership within each economy.

C is defined as the carbon intensity vector, and the carbon emissions matrix E is:

$$E = \widehat{C}(I - A)^{-1}\widehat{Y} = \widehat{C}B\widehat{Y} \tag{2}$$

Depending on whether the emissions are generated by pure domestic firms (D) or affiliates of foreign MNEs (F), or whether the emissions are generated to meet the needs of domestic firms or foreign affiliates, we can extend the decomposition framework as follows (see Fig. 1):

$$\begin{aligned} E = \hat{C}B\hat{Y} = & \underbrace{\underbrace{\hat{C}_D L^O \hat{Y}_D^L}_{\substack{Pure\ domestic \\ production \\ (1)\ E\_D}} + \underbrace{\hat{C}_D L^O \hat{Y}_D^E}_{\substack{Traditional \\ trade \\ (2)\ E\_RT}}}_{non-GVC\ activities} + \underbrace{\hat{C}_D (B^O - L^O)\hat{Y}_D}_{\substack{Trade-related\ GVCs \\ (3)\ E\_GVCT}} + \underbrace{\hat{C}_F L^O \hat{Y}_F + \hat{C}(L - L^O)\hat{Y}}_{\substack{FDI-related\ GVCs \\ (4)\ E\_GVCI}} \\ & + \underbrace{\hat{C}_F (B^O - L^O)\hat{Y}_F + \hat{C}((B - B^O) - (L - L^O))\hat{Y}}_{\substack{Trade-\ and\ FDI-related\ GVCs \\ (5)\ E\_GVCTI}} \end{aligned} \tag{3}$$

The new decomposition framework[1] considers the industrial linkages between domestic and foreign companies within a single country and divides this kind of activity into FDI-related GVC activities. In equation (3), $\widehat{C}_D L^O \widehat{Y}_D^L$ and $\widehat{C}_D L^O \widehat{Y}_D^E$ are the emissions embodied in pure domestic production and traditional trade, respectively. These emissions are generated from non-GVC activities. $\widehat{C}_D (B^O - L^O) \widehat{Y}_D$ represents the emissions only originating from trade-related GVC activities; $\widehat{C}_F L^O \widehat{Y}_F$ and $\widehat{C}(L - L^O)\widehat{Y}$ are the emissions originating only from FDI-related GVC activities; $\widehat{C}_F (B^O - L^O)\widehat{Y}_F$ and $\widehat{C}((B - B^O) - (L - L^O))\widehat{Y}$ are the emissions originating from GVC activities related to trade and FDI.

[1] For details, please refer to Appendix B.

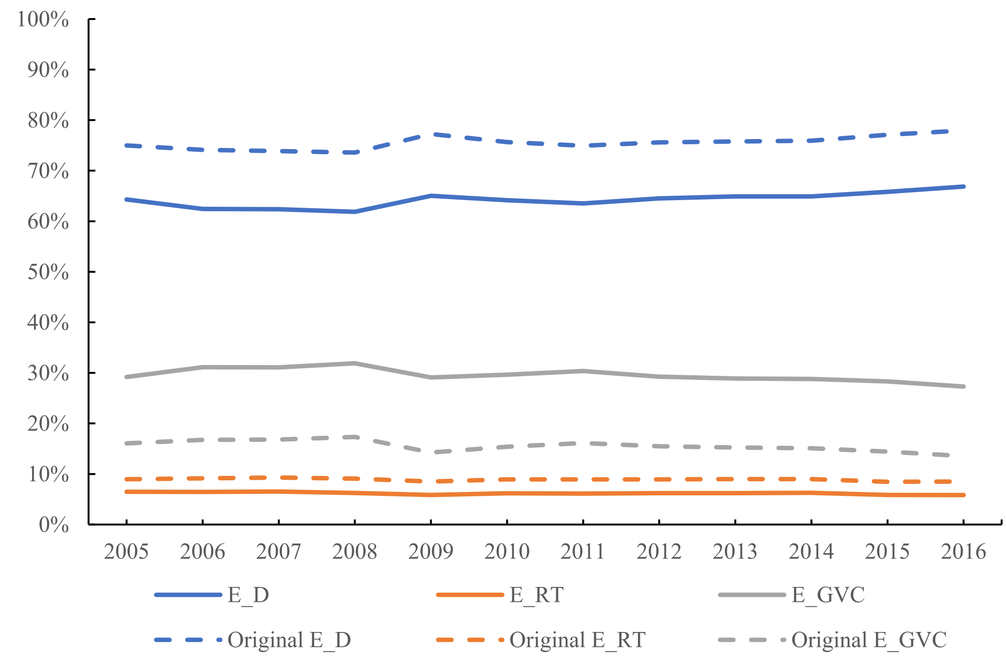

Fig. 2. Emissions originating from production under the different frameworks.

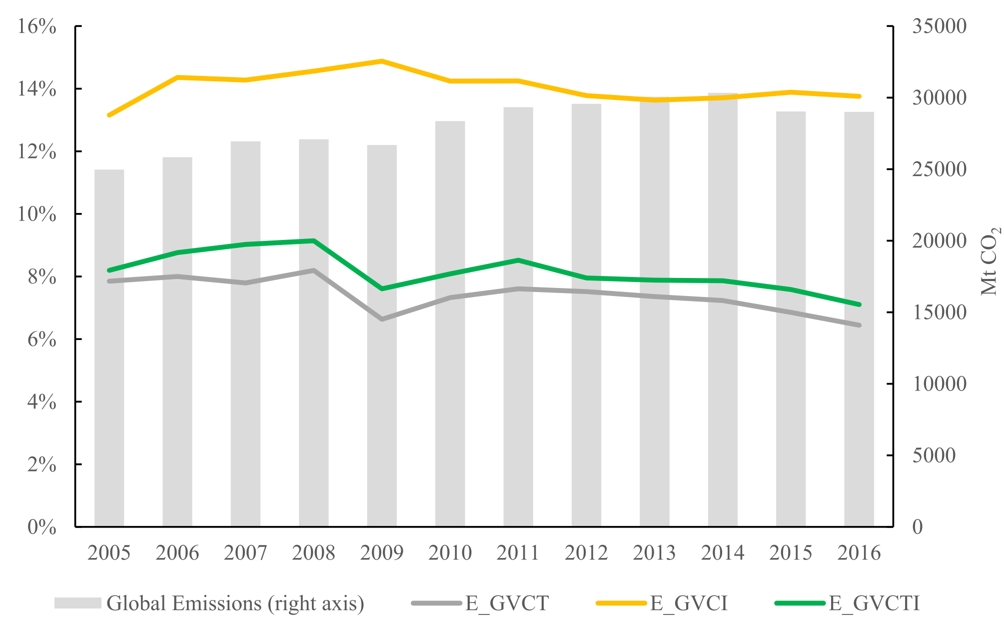

Fig. 3. Share of the emissions from different activities in the global emissions.

Here, we mainly focus on the emissions originating only from FDI-related GVC activities, and this term can be divided into three parts according to the trade type and ownership of the supplier: (1) the emissions embodied in the pure domestic production chain of MNEs (E_GVCI_P); (2) the emissions embodied in the joint domestic production chain of domestic firms and MNEs, with MNEs in the upstream (E_GVCI_UF); (3) the emissions embodied in the joint domestic production chain of domestic firms and MNEs, with domestic firms in the upstream (E_GVCI_UD).

$$E\_GVCI = \underbrace{\hat{C}_F L^O \hat{Y}_F}_{(4-1)E\_GVCI\_P} + \underbrace{\hat{C}_F (L - L^O)\hat{Y}}_{(4-2)E\_GVCI\_UF} + \underbrace{\hat{C}_D (L - L^O)\hat{Y}}_{(4-3)E\_GVCI\_UD} \quad (4)$$

We apply structural decomposition analysis (SDA) to analyze the driving factors of the change in carbon emissions distinguishing domestic firms and MNEs. We propose a decomposition model of the change in carbon emissions embodied in FDI.

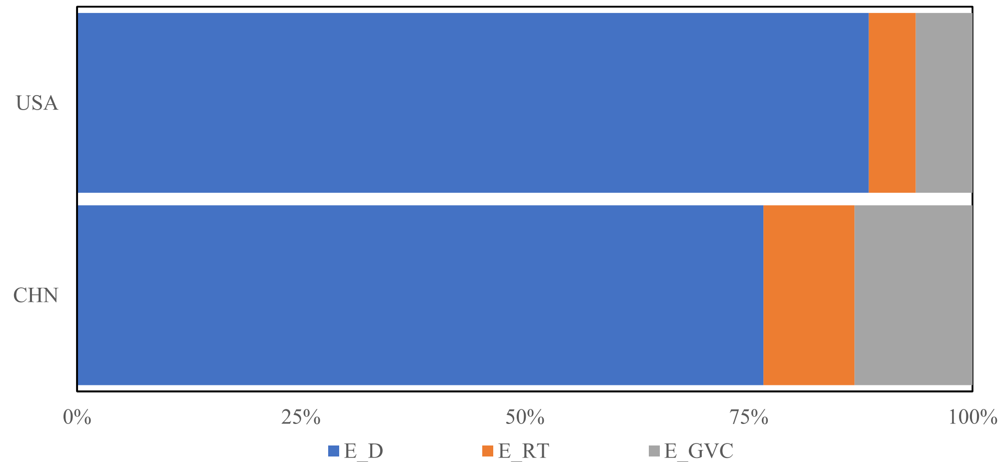

Fig. 4.1. Share of the emissions originating from different activities in China and USA, 2009: based on the authors' calculations using the method of Meng et al. [8].

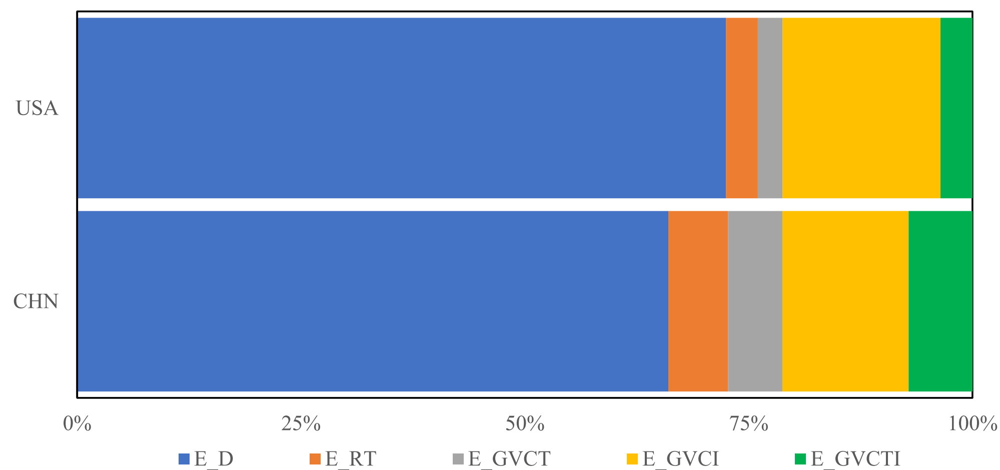

Fig. 4.2. Share of the emissions originating from different activities in China and USA, 2009: based on the authors' calculations with the new method Note: The results in Fig. 4.1 are calculated by the authors with data retrieved from the OECD AMNE database based on the method of Meng et al. [8].

$$\begin{aligned}\Delta E\_GVCI &= \left(\widehat{C}_{F1}L_1^O\widehat{Y}_{F1} + \widehat{C}_1\left(L_1 - L_1^O\right)\widehat{Y}_1\right) - \left(\widehat{C}_{F0}L_0^O\widehat{Y}_{F0} + \widehat{C}_0\left(L_0 - L_0^O\right)\widehat{Y}_0\right) \\ &= \frac{1}{2}\Delta\widehat{C}_F\left(L_1^O\widehat{Y}_{F1} + L_0^O\widehat{Y}_{F0}\right) + \frac{1}{2}\left(\Delta\widehat{C}_D + \Delta\widehat{C}_F\right)\left[\left(L_1 - L_1^O\right)\widehat{Y}_1 + \left(L_0 - L_0^O\right)\widehat{Y}_0\right] \\ &+ \frac{1}{2}\left(\widehat{C}_{F1}\Delta L^O\widehat{Y}_{F1} + \widehat{C}_{F0}\Delta L^O\widehat{Y}_{F0}\right) + \frac{1}{2}\left[\widehat{C}_1\Delta\left(L - L^O\right)\widehat{Y_0} + \widehat{C}_0\left(L - L^O\right)\widehat{Y_1}\right] \\ &+ \frac{1}{2}\left(\widehat{C}_{F1}L_1^O + \widehat{C}_{F0}L_0^O\right)\Delta\widehat{Y}_F + \frac{1}{2}\left[\widehat{C}_1\left(L_1 - L_1^O\right) + \widehat{C}_0\left(L_0 - L_0^O\right)\right]\left(\Delta\widehat{Y}_D + \Delta\widehat{Y}_F\right)\end{aligned} \tag{5}$$

where Δ represents the change between two periods. The first to third rows indicate the carbon intensity effect, structure effect and scale effect, respectively.

This paper relies on a public database constructed by the OECD, including the ICIO tables (2019 version), which distinguishes domestic firms and MNEs in 60 countries and 34 industries from 2005 to 2016[2]. The carbon emissions by country and industry are retrieved from the International Energy Agency (IEA), and we followed Zhang et al. [6] to split them by firm type, which is divided into CO_2 emissions of domestic firms and MNEs. The specific method is to employ the intermediate use of two energy-related industries "Mining and extraction of energy producing products" and "Coke and refined petroleum products" in monetary terms to proportionally decompose carbon emissions by firm types.

[2] The MNEs in the table only include foreign affiliates (firms with at least 50% foreign ownership) in the economies of the host countries; https://www.oecd.org/sti/ind/analytical-AMNE-database.htm.

Table 2
Emissions originating from different activities in the economies, by income level.

Year	Income Level	E_D	E_RT	E_GVC		
				E_GVCT	E_GVCI	E_GVCTI
2005	Lower middle income	70.7%	7.2%	7.3%	8.4%	6.4%
	Upper middle income	61.7%	7.1%	9.4%	12.8%	9.1%
	High income	65.4%	5.2%	5.2%	16.7%	7.5%
2016	Lower middle income	73.5%	7.1%	6.6%	8.0%	4.8%
	Upper middle income	66.4%	5.9%	6.7%	13.6%	7.4%
	High income	62.6%	5.5%	5.9%	18.1%	7.9%

Note: The level of income of a single economy is classified by the World Bank (refer to Appendix A), and the economies are divided into three categories: lower-middle-income, upper-middle-income and high-income. Rest of the world (Row) is not included here.

3. Results

3.1. Comparison of decomposition results under two frameworks

According to the decomposition method in section 2, we calculated the proportion of the emissions originating from different activities in the global emissions and revealed the difference between the new calculation results and the original results. Compared to the traditional method treating the emissions embodied in trade as the only source of emissions stemming from GVC activities, the scale and trend of the CO_2 emissions originating from GVC activities considering FDI (E_GVC) were largely different. Obviously, if FDI was not considered, the carbon emissions originating from GVC activities were underestimated by approximately 13.8 percentage points in 2016, that is to say, 13.8% of the total carbon emissions was neglected in the calculation of carbon emissions induced by GVC activities under the original decomposition framework. Approximately 11.1 percentage points of the carbon emissions stemming from pure domestic production (E_D) and 2.7 percentage points of the carbon emissions originating from traditional Ricardian trade (E_RT) were overestimated.

Combined with Figs. 2 and 3, from the perspective of the emissions from different production activities, pure domestic production has always been the main source of global emissions. The emissions embodied in trade accounted for about 8% of the total emissions, while the emissions embodied in FDI (E_GVCI) accounted for a much higher proportion of about 14%. If emissions embodied both in trade and FDI (E_GVCTI) are taken into consideration, the impact of investment activities on global carbon emissions will be more prominent. From 2005 to 2016, the global emissions increased by 4035.3 million tons. This change was mainly caused by GVC activities and pure domestic production activities. Among these emissions, 17.5% was caused by FDI, while international trade yielded a negative effect. Moreover, during the crisis period, the proportion of the emissions embodied in trade substantially decreased, while the emissions embodied in investment slightly increased. This indicates that investment could offset the negative impact of trade decline on the economy to a certain extent during the crisis period. Thus, when assessing the global emissions from GVC activities, the emissions embodied in FDI should be included, and the responsibilities should be correspondingly assumed by MNEs (and their controlling countries).

A similar situation is also observed at the national level. Taking the two largest international trade and carbon emitters, China and the United States as examples, we recalculated the emissions of China and USA along different routes (Fig. 4.2). Compared to the results obtained with the method of Meng et al. [8] in Fig. 4.1, the characteristics of the emissions of China and USA were basically similar in 2009: most emissions were generated to meet the domestic demand, indicating that the results are generally reasonable. After further dividing the carbon emissions generated by GVC activities, we observed several interesting phenomena: 1) The carbon emissions generated by GVC activities in USA were greatly underestimated (approximately 18 percentage points), most of which was attributed to misjudgement of the emissions generated to satisfy domestic needs; 2) traditional final trade in China was largely driven by MNEs, so that the conclusion 'the share of CO_2 emissions induced by foreign final demand through final goods trade in China was obviously larger than that in USA' obtained by Meng et al. [8] was inconsequential.

At the global and national levels, the carbon emissions embodied in MNEs' investment, which account for a relatively large proportion of the

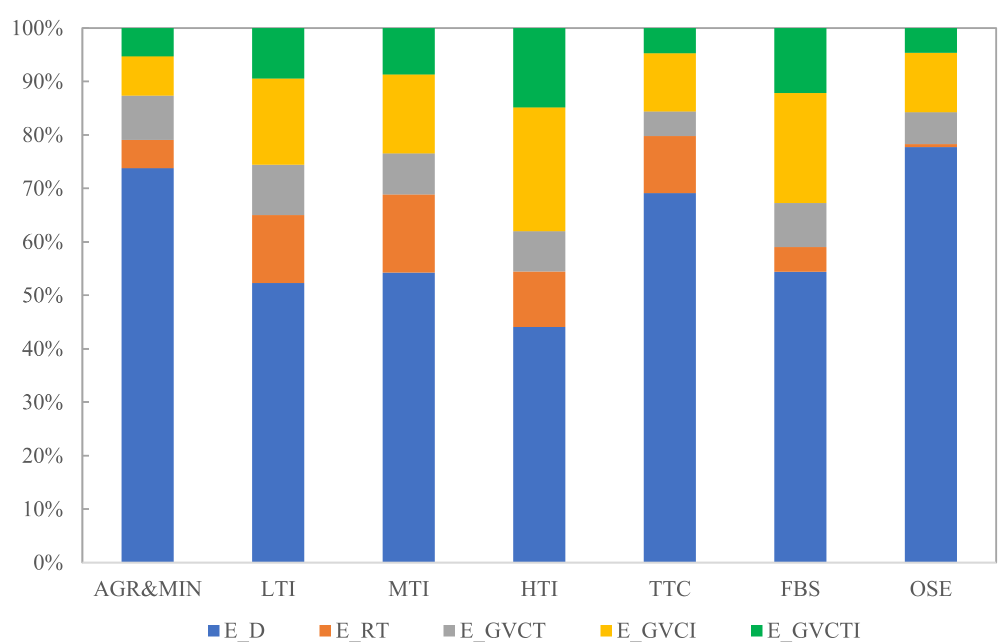

Fig. 5. Emissions originating from the different activities in representative sectors, 2016 Note: The sectors are classified according to the industry classification standards issued by the OECD (refer to Appendix A).

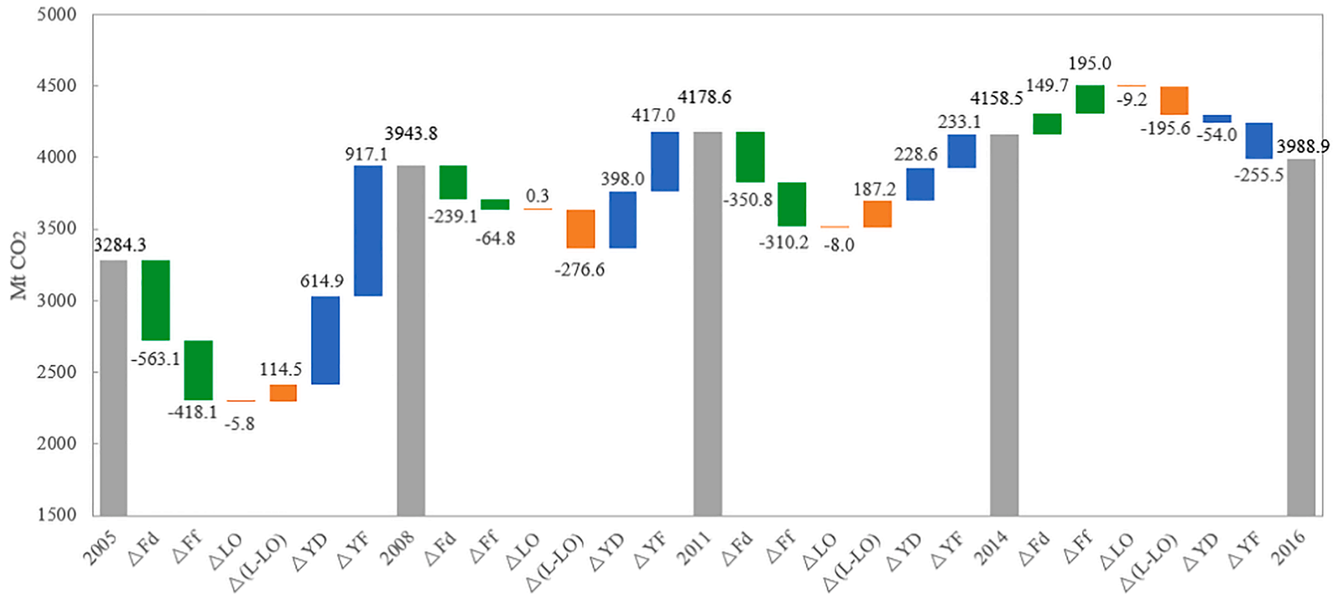

Fig. 7. Changes in FDI-related GVC emissions during the different subperiods: 2005–2008, 2008–2011, 2011–2014 and 2014–2016 Note: The grey parts represent the scale of FDI-related GVC emissions throughout the year. The green, orange and blue parts represent the carbon intensity effect (of domestic firms and MNEs), production structure effect (of firms with the same and different ownerships) and scale effect (of domestic firms and MNEs), respectively.

Table 3
FDI-related GVC emissions of the economies, by income level.

Year	Income Level	E_GVCI/total emissions	E_GVCI		
			E_GVCI_P	E_GVCI_UF	E_GVCI_UD
2005	Lower middle income	8.4%	23.3%	24.7%	52.0%
	Upper middle income	12.8%	19.5%	25.9%	54.7%
	High income	16.7%	29.9%	31.6%	38.5%
2016	Lower middle income	8.0%	20.9%	22.7%	56.4%
	Upper middle income	13.6%	15.7%	22.1%	62.1%
	High income	18.1%	35.2%	30.4%	34.4%

total carbon emissions, are often neglected. To accurately evaluate the real carbon emissions of a single economy from the perspective of GVCs, we should pay attention to the emissions embodied in FDI when considering the carbon emissions structure of production activities.

3.2. Emissions originating from different activities in representative economies and sectors under the new framework

The FDI-related GVC emissions vary significantly among different economies and industries. This is related to the degree of economic development and nature of the industry rather than the overall scale of the carbon emissions. As indicated in Table 2, the FDI-related emissions originating from GVC activities in high-income economies accounted for a higher proportion of the total emissions (18.1% in 2016) than that in upper-middle-income and lower-middle-income economies (13.6% and 8.0%, respectively, in 2016). In addition, high-income economies prefer to promote production by attracting investment rather than via global trade. The difference between FDI-related GVC emissions and trade-related GVC emissions in the high-income group (12.3% in 2016) was much larger than that in the upper-middle-income group (6.9% in 2016) and lower-middle-income group (1.4% in 2016). Assessing the change in FDI-related GVC emissions from 2005 to 2016, the proportions in the high-income group and upper-middle-income group had risen 1.5% and 0.9%, respectively, while that in the lower-middle-income group had remained basically unchanged. This suggests that the extent to which MNEs are embedded in local production chains through FDI is deepening. Therefore, considering FDI-related GVC emissions has a more important impact on the reevaluation of the carbon emissions of high-income economies.

When we focus on the structure of the carbon emissions from different value chain activities within a single industry, we find that regardless of either FDI-related GVCs or trade-related GVCs, MNEs play a more obvious role in manufacturing (see Fig. 5). The proportion of the emissions stemming from FDI-related GVC activities in the manufacturing industry was higher than that in the agriculture, mining, and service industries, accounting for 20% of the total carbon emissions of the industry. Within the manufacturing industry, the higher the level of technology, the more the emissions stemming from GVC activities were underestimated. In 2016, the FDI-related GVC emissions in the high-tech manufacturing sector accounted for approximately 23.2% of the total emissions of the industry, while the proportion of the low-tech and medium-tech manufacturing sectors was lower than 16%. It should be noted that the proportion of FDI-related GVC emissions in the low-tech manufacturing sectors was higher than that in the medium-tech manufacturing sectors. This may occur because some FDI flows into basic manufacturing tasks or low-tech manufacturing sectors with high carbon emissions. The expansion of consumption in such labor-intensive industries (such as textiles, wearing apparel, leather and related products) stimulates the production of upstream sectors and generates higher emissions. In the service industry, the carbon emissions were also highly underestimated. The emissions embodied in FDI were far higher than those embodied in trade, with the former approximately 2.26 times the latter. Because many modern investment and commercial banks and business service companies have established branches in multiple countries, the emissions stemming from their investment activities resulted in an underestimation of over 20 percentage points.

3.3. Decomposition of FDI-related GVC emissions

In order to determine the routes whereby FDI mainly promotes GVC

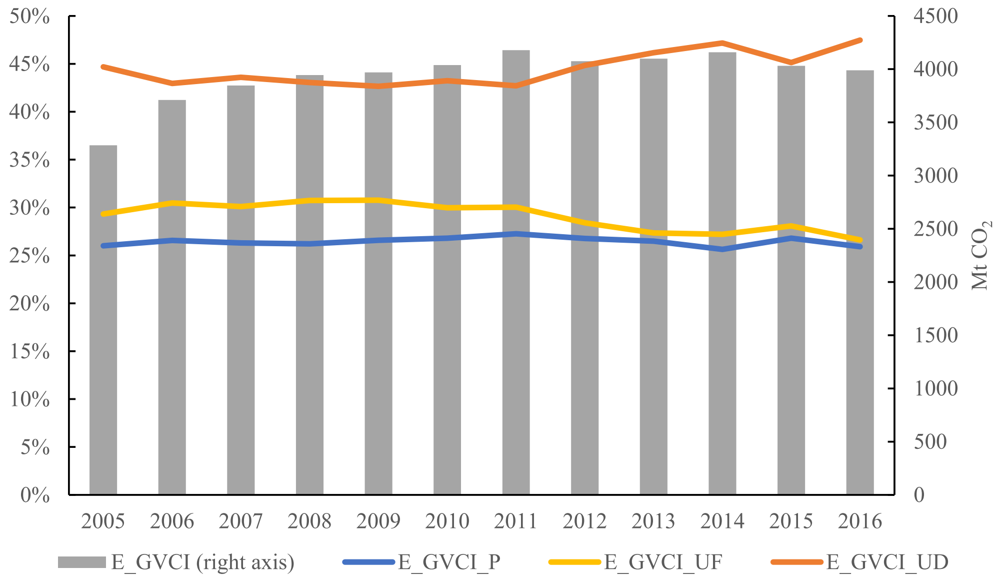

Fig. 6. Structure of FDI-related GVC emissions.

emissions, we further measured the composition of FDI-related GVC emissions. The FDI-related GVC emissions include three parts: the emissions embodied in the pure domestic production chain of MNEs; the emissions embodied in the joint domestic production chain of domestic firms and MNEs, with MNEs in the upstream; the emissions embodied in the joint domestic production chain of domestic firms and MNEs, with domestic firms in the upstream. According to Fig. 6, the emissions generated by domestic firms acting as upstream suppliers in the joint domestic production chain accounted for 47.5% of the FDI-related GVC emissions, and the emissions generated by MNEs in the domestic production chain accounted for 52.5% of the FDI-related GVC emissions in 2016 (25.9% through the pure domestic production chain and 26.6% through the joint domestic production chain). MNEs' investment mainly drives the production of upstream domestic firms through the industrial linkage between domestic firms and MNEs, thereby increasing the carbon emissions of upstream industries, but exerts little direct impact on the carbon emissions originating from the domestic production chain only between MNEs.

There are obvious structural differences in FDI-related GVC emissions between the economies with different income levels (see Table 3). In 2016, the FDI-related GVC emissions of lower-middle-income economies were mainly generated by the joint domestic production chains, with domestic firms (E_GVCI_UD) and MNEs (E_GVCI_UF) in the upstream accounting for 56.4% and 22.7%, respectively. The emissions stemming from the pure domestic production chains of MNEs (E_GVCI_P) accounted for only 20.9% of the FDI-related GVC emissions. This feature was even more obvious in the upper-middle-income economies, with the proportion of emissions stemming from the joint domestic production chains reaching 84.3%. However, the three types of emissions in the high-income economies accounted for relatively equal proportions. FDI mainly drove the production emissions of MNEs (65.6%), especially through the joint domestic production chain (35.2%).

In the high-income economies, the proportion of emissions stemming from FDI increased by 1.5% from 2005 to 2016. This change was mainly caused by the pure domestic production activities of MNEs, suggesting that the impact of FDI on local upstream MNEs had gradually strengthened. In the upper-middle-income and lower-middle-income economies, the driving effect of FDI on the emissions of upstream domestic firms had considerably increased, with that in the lower-middle-income group rising by 4.4% and that in the upper-middle-income group rising by 7.5%. It could be seen that FDI might play an irreplaceable role in technological progress and industrial structure optimization of pure domestic firms in the upper-middle-income and lower-middle-income economies.

4. Trends and driving factors of FDI-related GVC emissions

From 2005 to 2016, the global carbon emissions increased by 4035.3 million tons, of which FDI-related GVC emissions increased by 704.6 million tons. The contribution of FDI to changes in the global carbon emissions cannot be ignored (17.46%). Therefore, we further analyzed the driving factors of the changes in FDI-related GVC emissions induced by the investment activities of MNEs. Fig. 7 shows the structural decomposition results during the different subperiods. In general, the main factor causing a decline in the emissions embodied in FDI was the carbon intensity effect, while the main factor promoting its rise was the scale effect of domestic firms (except from 2014 to 2016). The industry linkages between domestic firms and MNEs would yield a certain impact on the emissions embodied in FDI in a few years, but the production structure effect was not the main driving factor.

During the different time periods, the effect of MNEs changed greatly. During the period of rapid economic development from 2005 to 2008, the FDI-related GVC emissions sharply increased from 3284.3 million tons to 3943.8 million tons, with the carbon intensity of domestic firms as the main factor contributing to the emissions decline. The decline in the carbon intensity of MNEs exerted a much smaller impact on the emissions embodied in FDI than that exerted by the decline in the carbon intensity of domestic firms. A large amount of the local demand promoted the increase in FDI-related GVC emissions, and the scale effect of MNEs played a key role. During the crisis period and the subsequent recovery period from 2008 to 2011, the FDI-related GVC emissions increased slightly. The increase in FDI-related GVC emissions caused by the scale effect was larger than the reduction in FDI-related

GVC emissions caused by the structural effect and intensity effect. From 2011 to 2014, with increasing FDI, the carbon intensity effect of MNEs increased significantly. However, during this period, the final demand (especially the part of the local demand satisfied by MNEs) slowed down in pulling the carbon emissions embodied in FDI. The impacts of these three effects basically offset each other, and the emissions embodied in FDI remained basically unchanged. From 2014 to 2016, with the world economy still in the process of in-depth adjustment after the international financial crisis, the problems related to the economic structural imbalance in each economy had not yet been resolved, and the FDI-related GVC emissions declined. The carbon emission coefficient of several high-emission sectors had increased to a certain extent, which was a very prominent phenomenon in the high-emission sectors of MNEs. The emission coefficients of the electricity, gas, water supply, sewerage, waste and remediation services, chemicals and pharmaceutical products, transportation and storage sectors of MNEs notably increased, leading to an increase in carbon emissions. However, the scale and structural effects greatly reduced emissions, which might be caused by the sharp decline in the demand of MNEs as well as the shrinking international trade and investment. The decrease in FDI-related GVC emissions attributed to this effect exceeded the increase in FDI-related GVC emissions attributed to the intensity effect.

5. Conclusions

As the main carrier of trade flows in global value chains, multinational enterprises also contribute to or participate in the value chains through foreign direct investment and information transfer. However, the existing framework only focuses on international trade while overlooks foreign direct investment in global value chain accounting, resulting in an underestimation of the overall level of global value chain activities. This article re-decomposes production activities and proposes an Inter-Country Input-Output accounting framework that can distinguish domestic firms and multinational enterprises. We put forward the concept of "carbon emissions embodied in foreign direct investment" (FDI-related GVC emissions) and incorporates it into the carbon footprint of global value chain activities.

We found that 1) under the original decomposition framework, the carbon emissions stemming from global value chain activities were underestimated by about 13.8 percentage points in 2016, of which the majority was divided into the emissions originating from pure domestic production. A similar situation is also observed at the national level. The carbon emissions stemming from global value chain activities in USA were greatly underestimated (approximately 18 percentage points); 2) due to more active investment activities, the carbon emissions in high-income economies and high-tech manufacturing sectors were highly underestimated; 3) we further measured the composition of FDI-related GVC emissions to determine the routes whereby foreign direct investment mainly promotes emissions originating from global value chain activities. The results showed that foreign direct investment mainly drove the emissions of upstream domestic firms through the joint domestic production linkage between domestic firms and multinational enterprises, especially in upper-middle-income and lower-middle-income economies; 4) the main factors influencing the carbon emissions embodied in foreign direct investment were the carbon intensity and final demand from 2005 to 2016. The former reduced carbon emissions, while the latter caused carbon emissions to increase. Using the production-based accounting method considering heterogeneity of enterprises, this article reconfirms the emission of global value chain activities of economies and the sectors as well as the impact of foreign direct investment to support policy decisions on national emission responsibilities and quotas determination, differentiated foreign investment decisions, and cleaner production development.

Identifying the degree of misestimation of carbon emissions of each economy, and providing a way to accurately measure the emission responsibilities of each economy. In the era when more and more countries have put forward the goal of "carbon peak and carbon neutrality", carbon emission reduction is increasingly imperative. "How much emissions exist, who will reduce them, and how much emissions will be reduced" has become an urgent issue to be solved. Proper accounting of greenhouse gas emissions is essential for understanding its contribution to global climate change and providing information for mitigation of greenhouse gas emissions. At present, the common method for compiling inventories comes from the "IPCC Guidelines for National Greenhouse Gas Inventory" (such as the United Nations Framework Convention on Climate Change, UNFCCC [38]). It calculates the carbon emissions generated within the national territory from the perspective of production, and finds the key economies and sectors that directly emit a large amount of carbon emissions. However, due to the cross-border flow of production factors of multinational enterprises, the responsibilities for these emissions should be assumed by multinational enterprises themselves and corresponding controlling countries. Based on the perspective of the host country, this article analyzed the carbon emissions embodied in investment of multinational enterprises to explore the degree of misestimation of the emission responsibilities of each economy, and to provide a feasible idea for accurately determining emission curbs and rationally allocating emission quotas in the future.

Supporting for countries to formulate differentiated policies to attract foreign investment. The characteristics of the carbon emissions embodied in foreign direct investment in the economies with different income levels were inconsistent. Therefore, the government should consider the actual situation of the economy when formulating policies to attract foreign investment. Although foreign direct investment has an obvious driving effect on the overall production of high-income economies, the driving effect of foreign direct investment on the emissions of upstream domestic firms in high-income economies is not obvious. It shows that the production patterns of domestic firms and multinational enterprises in developed economies are basically independent of each other, and the affiliates of multinational enterprises have a relatively low degree of integration into their local production chains. The local government needs to balance the competitive relationship between multinational enterprises and domestic firms, as well as the benefits and environmental costs brought by foreign direct investment. In contrast, the inflow of foreign capital has a significant impact on domestic firms in upper-middle-income and lower-middle-income economies. Hence, these countries should take measures to strengthen cooperation between domestic firms and multinational enterprises in local value chains, actively absorb the positive spillover effects of global value chain activities, and apply external investment to increase their own production capacity.

Promoting the clean production of enterprises and providing scientific evidence for the design of specific emission reduction measures. Within the manufacturing industry, the higher the level of technology, the more the emissions stemming from global value chain activities were underestimated. The FDI-related GVC emissions in the high-tech manufacturing sector accounted for approximately 23.2% of the total emissions of the industry in 2016. The rapid development of digital technology has provided an opportunity for the transformation and upgrading of the global manufacturing industry. Increasing foreign direct investment in high-tech manufacturing sectors could promote its development towards low-carbon, intelligent and advanced upgrading. During the development period, the main factor reducing the carbon emissions embodied in foreign direct investment is the change of carbon intensity. The government should consider vigorously introducing foreign investment with a high environmental value to further increase the share of clean industry in the economy structure. In addition, as the main source of advanced technologies in the world, multinational enterprises could transfer the technology through the internalization of foreign direct investment, which will have a positive external effect, that is, technology spillover effects, on the host country. Hence, it is necessary to strengthen the learning effect of domestic firms, improve their energy efficiency and promote the transformation from a high-carbon base to a low-carbon base. It is noted that there is a systematic difference between the participation of domestic firms and multinational enterprises in the global value chains. The host country should consider the heterogeneity of enterprises when setting emission limits and allocating green investment for target firms.

In addition, there are several points that require further discussion. Firstly, because investment in global value chains exhibits the advantages of a high stability, in the post-epidemic era when the epidemic and trade protectionism are rapidly developing, whether there will be a shift from trade-based global value chain activities to investment-based global value chain activities should urgently be investigated. With the adjustment and update of the multi-regional input–output data, we can look forward to the release of recent tables. It is also possible to use domestic and foreign production data to split the competitive input–output table of a single country and embed it in global databases such as WIOD\ADB\Eora\GTAP to analyze the changes in global value chain activities of representative countries (such as China and USA). Secondly, foreign direct investment has caused the transfer of global carbon emissions [6], but whether the pollution haven phenomenon occurs in which developed countries transfer high-carbon tasks to developing countries remains to be determined. Since the AMNE database cannot determine the sources of investment of multinational enterprises, we can use bilateral investment data to measure the changes in carbon emissions due to investment, by calculating the global carbon emissions if the output enabled by the investment of multinational enterprises is produced in the home country. Considering the availability of data, we can conduct research from the perspective of the United States. We can combine the US foreign direct investment data released by the US Bureau of Economic Analysis (BEA) and the world input–output table to examine the impact of international investment on the direction of global carbon emissions transfer. Thirdly, global value chains are more of a regional phenomenon today. Many countries have signed bilateral and multilateral agreements on trade and investment, such as the China-EU Bilateral Investment Treaty (BIT), the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP), and the Belt and Road Initiative (Belt and Road). The signing of regional trade and investment agreements yields an important impact on the carbon emissions reduction process of a single country and even the world, and any disputes between home countries and host countries may spread to the environmental field.

Credit authorship contribution statement

Kunfu Zhu: Conceptualization, Methodology, Writing – review & editing. **Xuefan Guo:** Data curation, Formal analysis, Writing – original draft. **Zengkai Zhang:** Data curation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Country and sector classification

See Tables A1 and A2

Table A1
Country classification.

Country Code	Country Name	Income Group	Country Code	Country Name	Income Group
ARG	Argentina	Upper middle	JPN	Japan	High
AUS	Australia	High	KHM	Cambodia	Lower middle
AUT	Austria	High	KOR	Korea, Rep.	High
BEL	Belgium	High	LTU	Lithuania	High
BGR	Bulgaria	Upper middle	LUX	Luxembourg	High
BRA	Brazil	Upper middle	LVA	Latvia	High
BRN	Brunei Darussalam	High	MAR	Morocco	Lower middle
CAN	Canada	High	MEX	Mexico	Upper middle
CHE	Switzerland	High	MLT	Malta	High
CHL	Chile	High	MYS	Malaysia	Upper middle
CHN	China	Upper middle	NLD	Netherlands	High
COL	Colombia	Upper middle	NOR	Norway	High
CRI	Costa Rica	Upper middle	NZL	New Zealand	High
CYP	Cyprus	High	PER	Peru	Upper middle
CZE	Czech Republic	High	PHL	Philippines	Lower middle
DEU	Germany	High	POL	Poland	High
DNK	Denmark	High	PRT	Portugal	High
ESP	Spain	High	ROU	Romania	Upper middle
EST	Estonia	High	RUS	Russian	Upper middle
FIN	Finland	High	SAU	Saudi Arabia	High
FRA	France	High	SGP	Singapore	High
GBR	United Kingdom	High	SVK	Slovak Republic	High
GRC	Greece	High	SVN	Slovenia	High
HKG	Hong Kong SAR, China	High	SWE	Sweden	High
HRV	Croatia	High	THA	Thailand	Upper middle
HUN	Hungary	High	TUN	Tunisia	Lower middle
IDN	Indonesia	Lower middle	TUR	Turkey	Upper middle
IND	India	Lower middle	TWN	Chinese Taipei	High
IRL	Ireland	High	USA	United States	High
ISL	Iceland	High	VNM	Vietnam	Lower middle
ISR	Israel	High	ZAF	South Africa	Upper middle
ITA	Italy	High	ROW	Rest of World	–

Note: Country/region abbreviation comes from ISO 3166-1 alpha-3 standard. For a complete list, see in https://unstats.un.org/unsd/tradekb/knowledgebase/country-code.
The country group according to the income is classified by World Bank, see in https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.

Table A2
Sector classification.

Sector Code	Sector Description	Sector Group
A	Agriculture, forestry and fishing	AGR
B	Mining and extraction of energy producing products	MIN
C10T12	Food products, beverages and tobacco	LTI
C13T15	Textiles, wearing apparel, leather and related products	LTI
C16	Wood and products of wood and cork	LTI
C17T18	Paper products and printing	LTI
C19	Coke and refined petroleum products	LTI
C20T21	Chemicals and pharmaceutical products	HTI
C22	Rubber and plastic products	MTI
C23	Other non-metallic mineral products	MTI
C24	Basic metals	MTI
C25	Fabricated metal products	MTI
C26	Computer, electronic and optical products	HTI
C27	Electrical equipment	HTI
C28	Machinery and equipment, nec	HTI
C29	Motor vehicles, trailers and semi-trailers	HTI
C30	Other transport equipment	HTI
C31T33	Other manufacturing; repair and installation of machinery and equipment	LTI
DTE	Electricity, gas, water supply, sewerage, waste and remediation services	OSE
F	Construction	OSE
G	Wholesale and retail trade; repair of motor vehicles	TTC
H	Transportation and storage	TTC
I	Accommodation and food services	TTC
J58T60	Publishing, audiovisual and broadcasting activities	TTC
J61	Telecommunications	FBS
J62T63	IT and other information services	FBS
K	Financial and insurance activities	FBS
L	Real estate activities	OSE
MTN	Other business sector services	FBS
O	Public admin. and defence; compulsory social security	OSE
P	Education	OSE
Q	Human health and social work	OSE
RTS	Arts, entertainment, recreation and other service activities	OSE
T	Private households with employed persons	OSE

Note: the basis for sector classification comes from OECD, divided into 8 industry groups. https://www.oecd.org/sti/inno/researchanddevelopmentstatisticsrds.htm. 1) AGR: Agriculture, forestry and fishing (01T03 in the ISIC Rev4); (2) MIN: Mining and quarrying (05T08 in the ISIC Rev4); (3) HTI: High R&D-intensive industries, expressed as high-tech manufacturing sector in the text (20T21, 26T29, 302, 304, 309, 303 in the ISIC Rev4); (4) MTI: Medium R&D-intensive industries, expressed as medium-tech manufacturing sector in the text (22T25, 301, less 325 in the ISIC Rev4); (5) LTI: low-level R&D-intensive industries, expressed as low-tech manufacturing sector in the text (10T19, 31T32 in the ISIC Rev4), (6) TTC: Trade and Transportation (45T53, 55T56, 58T60 in the ISIC Rev4); (7) FBS: Postal, Telecommunication, Financial and Business Services (61T66, 69T75 in the ISIC Rev4); (8) OSE: Real estate, public administration, construction and other services (35T39, 41T43, 68, 77T82, 84T88, 90T99 in the ISIC Rev4).

Appendix B. Methodology

We re-decompose the emissions model on the basis of distinguishing enterprise ownership.

$$E = \widehat{C}B\widehat{Y} = \widehat{C}L^{O}\widehat{Y} + \widehat{C}\left(L - L^{O}\right)\widehat{Y} + \widehat{C}\left(B^{O} - L^{O}\right)B^{O} - L^{O}\widehat{Y} + \widehat{C}\left(\left(B - B^{O}\right) - \left(L - L^{O}\right)\right)\widehat{Y} \tag{B.1}$$

In equation (B.1), $\left(L - L^{O}\right)$ is the domestic industry linkage between domestic firms and MNEs. $\left(B^{O} - L^{O}\right)$ is international industry linkage between firms with the same ownership, $\left(\left(B - B^{O}\right) - \left(L - L^{O}\right)\right)$ is international industry linkage between domestic firms and MNEs. We can further distinguish the carbon emission intensity and final use of domestic firms and MNEs:

Table B1
The decomposition framework based on forward industrial linkage.

Subject and Destination \ Activities		Pure Domestic Value Chain		Traditional in Final Goods		Trade in Intermediate Goods	
		Homogeneous Enterprise Association	Heterogeneous Enterprise association	Homogeneous Enterprise Association	Heterogeneous Enterprise association	Homogeneous Enterprise Association	Heterogeneous Enterprise association
Domestic firms	satisfy domestic firms' production	$\hat{C}_D L^O \hat{Y}_D^L$	$\hat{C}_D L^O \hat{Y}_D^E$	$\hat{C}_D (L-L^O)\hat{Y}_D^L$	$\hat{C}_D (L-L^O)\hat{Y}_D^E$	$\hat{C}_D (B^O-L^O)\hat{Y}_D$	$\hat{C}_D ((B-B^O) -(L-L^O))\hat{Y}_D$
	satisfy MNEs' production	—	—	$\hat{C}_D (L-L^O)\hat{Y}_F^L$	$\hat{C}_D (L-L^O)\hat{Y}_F^E$	—	$\hat{C}_D ((B-B^O) -(L-L^O))\hat{Y}_F$
MNEs	satisfy domestic firms' production	—	—	$\hat{C}_F (L-L^O)\hat{Y}_D^L$	$\hat{C}_F (L-L^O)\hat{Y}_D^E$	—	$\hat{C}_F ((B-B^O) -(L-L^O))\hat{Y}_D$
	satisfy MNEs' production	$\hat{C}_F L^O \hat{Y}_F^L$	$\hat{C}_F L^O \hat{Y}_F^E$	$\hat{C}_F (L-L^O)\hat{Y}_F^L$	$\hat{C}_F (L-L^O)\hat{Y}_F^E$	$\hat{C}_F (B^O-L^O)\hat{Y}_F$	$\hat{C}_F ((B-B^O) -(L-L^O))\hat{Y}_F$

$$\begin{aligned}
E = {} & \left(\widehat{C}_D + \widehat{C}_F\right) L^O \widehat{Y} + \left(\widehat{C}_D + \widehat{C}_F\right)(L - L^O)\widehat{Y} + \left(\widehat{C}_D + \widehat{C}_F\right) \\
& + \left(\widehat{C}_D + \widehat{C}_F\right)\left((B - B^O) - (L - L^O)\right)\widehat{Y} \\
= {} & \widehat{C}_D L^O \left(\widehat{Y}_D^L + \widehat{Y}_F^L + \widehat{Y}_D^E + \widehat{Y}_F^E\right) + \widehat{C}_F L^O \left(\widehat{Y}_D^L + \widehat{Y}_F^L + \widehat{Y}_D^E + \widehat{Y}_F^E\right) \\
& + \widehat{C}_D (L - L^O)\left(\widehat{Y}_D^L + \widehat{Y}_F^L + \widehat{Y}_D^E + \widehat{Y}_F^E\right) + \widehat{C}_F (L - L^O)\left(\widehat{Y}_D^L + \widehat{Y}_F^L + \widehat{Y}_D^E + \widehat{Y}_F^E\right) \\
& + \widehat{C}_D (B^O - L^O)\left(\widehat{Y}_D^L + \widehat{Y}_F^L + \widehat{Y}_D^E + \widehat{Y}_F^E\right) + + \widehat{C}_F (B^O - L^O)\left(\widehat{Y}_D^L + \widehat{Y}_F^L + \widehat{Y}_D^E + \widehat{Y}_F^E\right) \\
& + \widehat{C}_D \left((B - B^O) - (L - L^O)\right)\left(\widehat{Y}_D^L + \widehat{Y}_F^L + \widehat{Y}_D^E + \widehat{Y}_F^E\right) \\
& + \widehat{C}_F \left((B - B^O) - (L - L^O)\right)\left(\widehat{Y}_D^L + \widehat{Y}_F^L + \widehat{Y}_D^E + \widehat{Y}_F^E\right) \\
= {} & \widehat{C}_D L^O \widehat{Y}_D^L + \widehat{C}_D L^O \widehat{Y}_D^E + \widehat{C}_D (L - L^O)\widehat{Y}_D^L + \widehat{C}_D (L - L^O)\widehat{Y}_D^E + \widehat{C}_D (B^O - L^O)\widehat{Y}_D \\
& + \widehat{C}_D \left((B - B^O) - (L - L^O)\right)\widehat{Y}_D \\
& + \widehat{C}_D (L - L^O)\widehat{Y}_F^L + \widehat{C}_D (L - L^O)\widehat{Y}_F^E + \widehat{C}_D \left((B - B^O) - (L - L^O)\right)\widehat{Y}_F \\
& + \widehat{C}_F (L - L^O)\widehat{Y}_D^L + \widehat{C}_F (L - L^O)\widehat{Y}_D^E + \widehat{C}_F \left((B - B^O) - (L - L^O)\right)\widehat{Y}_D \\
& + \widehat{C}_F L^O \widehat{Y}_F^L + \widehat{C}_F L^O \widehat{Y}_F^E + \widehat{C}_F (L - L^O)\widehat{Y}_F^L + \widehat{C}_F (L - L^O)\widehat{Y}_F^E + \widehat{C}_F (B^O - L^O)\widehat{Y}_F \\
& + \widehat{C}_F \left((B - B^O) - (L - L^O)\right)\widehat{Y}_F
\end{aligned} \tag{B.2}$$

In equation (B.2), from column 2–5 to column 6–11, we merge and remove zero items. The details of decomposition framework show in Table B1. The blue part and orange part are emissions of domestic firms at both production side and consumption side, through homogenous industries to satisfy domestic need and traditional trade, which can be defined as Non-GVC Activities. The gray part is emissions of domestic firms at both production side and consumption side, but cross-border trade of intermediate products is conducted, which is emissions from GVC activities only related to trade (trade-related GVC emissions). The yellow part is emissions from GVC activities only related to the investment of MNEs (FDI-related GVC emissions), which is connected through domestic industry associations. The green part is emissions from GVC activities related to trade and investment (trade and FDI related GVC emissions).

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