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Tracing CO_2 Emissions in Global Value Chains: Multinationals vs. Domestically-owned Firms

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Abstract: This study integrates the new global value chain (GVC) accounting method that explicitly considers the difference in the production functions of multinational enterprises (MNEs) and domestically-owned firms into existing production- and consumption-based CO_2 emissions measures. This enables us to consistently trace emissions in GVCs through trade- and foreign direct investment (FDI)-related routes at the bilateral country-sector level by firm ownership. Based on OECD data, our empirical results, reveal that emissions related to FDI account for 15.2 percent of the world's total emissions and 58.1 percent of the world's GVCs emissions, 39.2 percent of which are emissions related to FDI for foreign demands in 2015. From 2000 to 2015, south–south emission transfers experienced rapid growth with relatively high carbon intensity. MNEs play a significant role through FDI in south countries, both in generating emissions as energy users and in transferring emissions as high-carbon intensive intermediate goods users in GVCs. There is a substantial difference in the patterns of emissions creation, transfer, and absorption in GVCs by firm ownership. These findings help us to better understand who creates emissions for whom and from which route and their potential environmental responsibility along GVCs.

Keywords: embodied carbon emissions; carbon footprint; global value chain; multinational enterprises; emission responsibility; GVC; FDI

JEL Classification: Q54; C67; F64

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1. Introduction

Due to the rapid development of global value chains (GVCs) over the last two decades (WTO-IDE, 2011; Degain et al., 2017; Li et al., 2019; Antràs and Gortari, 2020; ADB, 2021), the "Made in" label typically applied to manufactured goods, attributing them to a specific economy, has become an archaic symbol of a bygone era, as most manufactured goods are now "Made in the World" (that is, they are produced in stages in a number of countries, with value added at each stage). The phenomenon of GVCs, which have considerable benefits in the economic efficiency for multinational enterprises (MNEs) (Melitz and Trefler, 2012; Bloom et al., 2012), has significantly changed the nature and structure of international trade and investment (Gereffi and Fernandez-Stark, 2011; Baldwin and Gonzalez, 2015). A report by the United Nations Conference on Trade and Development (UNCTAD, 2013) stated that 80 percent of trade takes place in "value chains" linked to transnational corporations. Meanwhile, the increasing complexity and uncertainty of risk in GVCs have also created considerable difficulty in understanding "who creates value added and emissions or pollution for whom through which routes along GVCs." This makes it challenging to formulate policies that enable countries, industries, and firms to identify both their economic gains and environmental responsibilities in GVCs (Kander et al., 2015).

Regarding the connection between international trade and carbon emissions, a large body of literature has developed the concept of "consumption-based accounting" (Hoekstra and Wiedmann, 2014; Peters, 2008; Tukker and Dietzenbacher, 2013; Cadarso et al., 2018; Kander et al., 2016), with a strong emphasis on carbon emission transfer caused by developed countries' consumption of goods produced in developing countries. Similar applications can be found in many environmental issues, including climate change (Meng et al., 2018a; Jiborn et al., 2020; Davis et al., 2011), energy use (Owen et al., 2017), air pollution (Lin et al., 2014; Kanemoto et al., 2014), material use (Wiedmann et al., 2015), land use (Weinzettel et al., 2013), biomass (Peters et al., 2012), water (Feng et al., 2011; Lenzen et al., 2013; White et al., 2018), and biodiversity (Lenzen et al., 2012). This accounting framework has considerable methodological and conceptual overlap with studies on "trade in value-added" in relation to GVCs (Johnson and Noguera, 2012; Koopman et al., 2014; Timmer et al., 2014). However, few formal attempts have been made to link these two independent lines of research by explicitly considering both MNEs' trade and investment activities to measure the impact of production sharing of MNEs and identify their emission responsibility in GVCs.

Currently, the Paris Agreement focuses on territory-based emissions (which are easy to monitor), whereas consumption-based emissions are used as a reference when designing possible transnational financial support mechanisms to enable developed countries to help developing countries reduce their emissions. Unfortunately, neither territorial-based nor consumption-based accounting (both of which allocate full responsibility to either the producers or consumers) provide sufficient incentive for countries to pursue emissions reduction efforts because of a lack of consensus in responsibility sharing.

Although several pioneering studies have discussed producers and consumers sharing responsibility in emissions (Andrew and Forgie, 2008; Bastianoni et al., 2004; Cadarso et al., 2012; Ferng, 2003; Kondo et al., 1998; Gallego and Lenzen, 2005; Lenzen et al., 2007; Dietzenbacher et al., 2020; Rodrigues et al., 2006), three significant problems remain unresolved. One is how to identify and measure a country's pure self-responsibility for emissions in GVCs. Without an accurate measure, we cannot even determine the amount of emissions for which responsibility should be shared among the various parties involved. The second problem is how to determine the appropriate weights to enable the proper distribution of responsibility for emissions among the various producers and consumers along GVCs. The third problem is that analysis of both value-added (GDP) gain and emissions embodied in international trade in the existing literature rely heavily on territory-based measures (the border of the country) rather than the ownership or controlling power of firms. This may lead to misunderstandings in the identification of carbon leakages and emission responsibility sharing in a bilateral relationship. For example, numerous MNEs sold considerable amounts of products that were "made" or "assembled" in China through foreign direct investment (FDI) channels, to China's domestic consumers, but conventional trade measures do not count such sales as China's imports. Therefore, all the responsibility of emissions embodied in those domestic transactions belongs to China, regardless a production-based or consumption-based approach is followed.

In this paper, we first introduce a suitable accounting framework to trace both value added and emissions by firm ownership at each stage of the GVC from the perspectives of production, consumption, and FDI at the bilateral country-sector level. We also integrate the recent innovative studies of Meng et al. (2018a), Meng et al. (2020), and Wang et al. (2021) to trace emissions along GVCs with FDIs and affiliates of foreign MNEs. The use of our combined new framework enables us to clearly distinguish emissions of pure self-responsibility and emissions transfers (which can be narrowly defined as carbon leakage) through traditional trade routes and GVCs. Six types of emissions are clearly identified: The first type is emissions generated in purely domestic value chains that do not pass through international trade and FDI channels and only meet domestic final demand. The second type is the classic "cloth-for-wine" trade in which no GVC-related production sharing happens; it represents emissions generated by pure domestic production activities that meet foreign final demand. The third type is emissions produced by GVC activities, which can be further decomposed into four routes based on the type of international production sharing that occurs: these emissions are generated by trade-related activities; FDI-related activities for host country's market; FDI-related activities for global market; and both trade- and FDI-related GVC activities. This new accounting method enables better measure and monitor the path of emissions transfers and potential environmental costs (e.g., emissions per US dollar of value added created) along GVCs.

Applying this new accounting method to the OECD Activity of MNEs (AMNE) inter-country input-output (ICIO) data (Cadestin et al., 2018) in which both domestically-owned firms and affiliates of foreign MNEs' data are available, our empirical results reveal several findings: First, CO_2 emissions generated through pure domestic value chains without any production sharing (a type of pure self-responsibility) accounted for approximately 64.5 percent and 69.9 percent of the total CO_2 emissions of developed and developing countries in 2015, respectively. Second, GVC-related emissions accounted for 23.9 percent and 30.3 percent of the total production-based emissions in developing and developed countries, respectively. Third, emissions of FDI-related GVC activities account for 58.1 percent of the world's GVCs-related emissions and 15.2 percent of the world's total emissions, in which FDI for global markets contributes 39.2 percent of the world's GVCs-related emissions. Fourth, roughly half of trade-related, FDI-related, and trade-and-FDI-related emissions on the production side are embodied in the south–south or north–north trade, and the remaining half are embodied in the south–north or north–south trade. Fifth, south–south emissions transfers through FDI-related GVC activities experienced a rapid increase and are more carbon-intensive than those in pure domestic value-added production activities. This implies that through FDIs in the south countries, affiliates of foreign MNEs have played a significant role in both generating emissions as energy users and transferring emissions as intermediate goods users in GVCs. Sixth, there is substantial heterogeneity among the sectors in terms of the volume of emissions, the structure of GVCs routes, and the host countries' production patterns. The above findings not only help us to better understand how production sharing through both trade and FDI affects emissions in GVCs, but are also useful for relevant parties engaging in deep discussion on the distribution of shared responsibilities and its possible policy implications.

The rest of the paper is organized as follows. The next section presents the accounting method and source of data. The third section present the results at the aggregated, bilateral, and sectoral levels. The final section offers concluding remarks and potential policy implications.

2. Accounting method and source of data

To the best of our knowledge, only a few studies have introduced MNEs' or foreign-owned/foreign-invested firms' activities into measuring emissions transfers in GVCs. For example, Dietzenbacher et al. (2012) and Su et al. (2013) introduced information about a firm's involvement in the supply chain (processing and non-processing trade) into the estimation of embodied CO_2 emissions in Chinese exports and revealed that overestimation occurs when using conventional IO tables. However, they did not provide any explicit information about firm ownership. Employing an augmented Chinese national IO database, Jiang et al. (2015) used information about both firm ownership and type of trade to estimate embodied CO_2 emissions in Chinese exports in 2007. However, there is no explicit consideration of the overestimation of embodied emissions in Chinese exports from the upstream and downstream perspectives of global supply chains.

Liu et al. (2016) demonstrated that ignoring firm heterogeneity causes embodied CO_2 emissions in Chinese exports to be overestimated by 20 percent at the national level, with significant variations at the sector level. They also pointed out that the reason for the overestimation is that different types of firms that are allocated to the same sector in the conventional Chinese IO table vary greatly in terms of market share, production technology, and carbon intensity. Conducting detailed supply chain analysis, Meng et al. (2018b) combined firm size and ownership information to reveal that final demand for products manufactured at the downstream by domestic private small and medium-sized enterprises (SMEs) and exports manufactured at the downstream by foreign-owned SMEs are the main drivers of China's CO_2 emissions. They also found that most of these emissions occur at the upstream in the electricity and heating sector, which is mainly controlled by large state-owned enterprises with the highest carbon intensity, and the non-metallic mineral sector, which comprises a very large number of domestic private SMEs with low levels of enforcement of emissions regulations. Most studies that have considered carbon emissions in supply chains by firm ownership are about China; this is mainly due to the availability of the Chinese IO data with firm ownership information.

Recently, due to the availability of the OECD AMNE-ICIO data, Zhang et al. (2020) used it to trace the carbon footprints of foreign affiliates of MNEs and revealed that the gross volume of global carbon transfer through investment peaked in 2011; it was mainly driven by the decline in carbon intensity. They also pointed out that despite the declining carbon footprints of developed country-based MNEs, there has been a considerable increase in carbon transfer sourced from mainland China. Using the same OECD data, Duan et al. (2021) re-evaluated the role of MNEs in global CO_2 emissions against the risks of a reversal in economic globalization. They traced the generations of CO_2 emissions in global production chains by both MNEs and non-MNEs and simulated the global CO_2 emissions under anti-globalization scenarios with the reflow[1] of MNEs. Their results revealed that the global supply chain-based emission intensities of MNEs are higher than those of non-MNEs, whereas the direct intensities of MNEs are lower than those of non-MNEs. However, none of the previous studies that have focused on CO_2 emissions and GVCs have clearly identified GVC activities based on the pattern of production sharing at the bilateral country-sector levels within a production- and consumption-based accounting system.

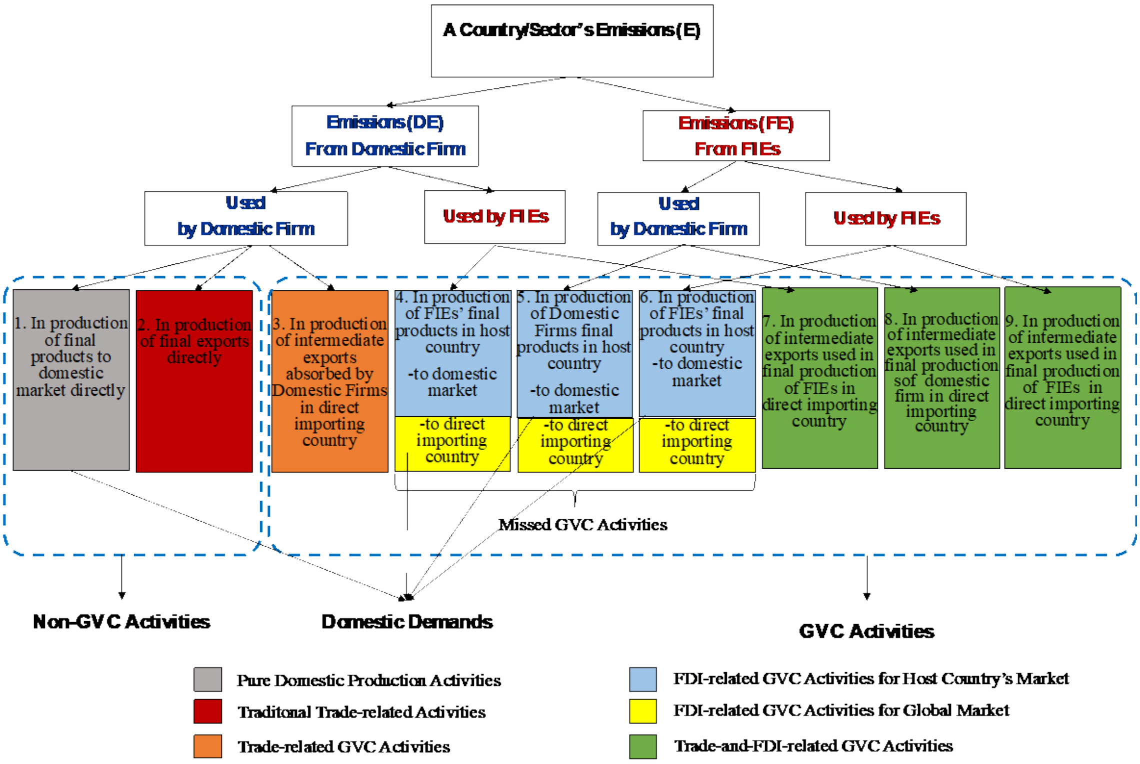

Figure 1. Forward-Tracing of a Country's Emissions in the GVC by Firm Ownership, Sector, and Country

[1] Duan et al. (2021) define an extreme reversal of globalization, under which the productions of MNEs were completely replaced by non-MNEs with a restructuring of supply chains, i.e., the large-scaled reflows of MNEs.

Following Meng et al. (2018a), which unified trade in value-added and embodied emissions in gross trade accounting framework (Koopman et al., 2014), and Wang et al. (2021), which introduced a unified framework to identify GVC activities by considering the difference in the production function of domestically-owned firms and foreign affiliates of MNEs, we introduce an accounting framework to trace both value added and emissions by firm ownership at each stage of the GVC from the perspectives of production, consumption, and FDI at the bilateral country-sector level. Using this accounting framework, we can clearly distinguish emissions of pure self-responsibility and emissions transfers through traditional trade routes and GVCs. The accounting framework, which is depicted in Figure 1, decomposes the country-sector emissions based on inter-industrial forward linkages according to different GVCs routes: pure domestic activities, traditional and GVC trade-related activities, FDI-related GVC activities for host country's market, FDI-related GVC activities for global market, and both trade-and-FDI-related activities.

Assume there are G economies and N industries, with two types of firms in each sector of the economy: domestically- and foreign-owned firms. Based on Meng et al. (2018a), a country or sector's total emissions can be decomposed as follows:

$$\hat{E}B\hat{Y} = \hat{E}L\hat{Y}^L + \hat{E}L\hat{Y}^E + \hat{E}LA^E L\hat{Y}^L + \hat{E}LA^E(B\hat{Y} - L\hat{Y}^L) \qquad (1)$$

where $\hat{E}$ denotes a G×N×2 by G×N×2 diagonal CO_2 emissions intensity matrix with elements of E at the diagonal; $\hat{Y}$ represents another G×N×2 by G×N×2 matrix of final production of each country, sector, or firm type pair; and A represents the value of intermediate inputs required to produce a unit of gross output by domestically-owned firms and MNEs. $\hat{Y}^L$ and A^L are the diagonal sub-matrices of $\hat{Y}$ and A, respectively; $\hat{Y}^E$ and A^E are off-diagonal sub-matrices of $\hat{Y}$ and A, respectively. $B = (I - A)^{-1}$ is the classical Leontief inverse matrix, and $L = (I - A^L)^{-1}$ is the local Leontief inverse. According to Equation (1), a country or sector's total emissions are decomposed into four parts: (1) the pure domestic part, $\hat{E}L\hat{Y}^L$, in which emissions are domestically produced and consumed; (2) the traditional final goods trade part, $\hat{E}L\hat{Y}^E$, in which emissions are embodied in exports of final goods and services; (3) the simple GVC part, $\hat{E}LA^E L\hat{Y}^L$, which includes emissions embodied in simple cross-country production sharing activities; and (4) the complex GVC part, $\hat{E}LA^E(B\hat{Y} - L\hat{Y}^L)$, in which emissions are embodied in complex cross-country production sharing activities.

Following the study of Wang et al. (2021), the total emissions can be traced according to the source of production that generates emissions and their use in final production by firm type, which is either domestically- or foreign-owned.

$$\hat{E}B\hat{Y} = (\hat{E}_D + \hat{E}_F)L(\hat{Y}_D^L + \hat{Y}_F^L) + (E_D + \hat{E}_F)L\ (\hat{Y}_D^E + \hat{Y}_F^E)$$
$$+(\hat{E}_D + \hat{E}_F)LA^E L(\hat{Y}_D^L + \hat{Y}_F^L) + (\hat{E}_D + \hat{E}_F)LA^E[(B\hat{Y}_D - L\hat{Y}_D^L) + (B\hat{Y}_F - L\hat{Y}_F^L)] \quad (2)$$

which can be re-written as 16 parts as follows:

$$\hat{E}B\hat{Y} = \hat{E}_D L\hat{Y}_D^L + \hat{E}_D L\hat{Y}_D^E + \hat{E}_D LA^E L\hat{Y}_D^L + \hat{E}_D LA^E(B\hat{Y}_D - L\hat{Y}_D^L)$$
$$+\hat{E}_D L\hat{Y}_F^L + \hat{E}_D L\hat{Y}_F^E + \hat{E}_D LA^E L\hat{Y}_F^L + \hat{E}_D LA^E(B\hat{Y}_F - L\hat{Y}_F^L)$$
$$+\hat{E}_F L\hat{Y}_D^L + \hat{E}_F L\hat{Y}_D^E + \hat{E}_F LA^E L\hat{Y}_D^L + \hat{E}_F LA^E(B\hat{Y}_D - L\hat{Y}_D^L)$$
$$+\hat{E}_F L\hat{Y}_F^L + \hat{E}_F L\hat{Y}_F^E + \hat{E}_F LA^E L\hat{Y}_F^L + \hat{E}_F LA^E(B\hat{Y}_F - L\hat{Y}_F^L) \quad (3)$$

Table 1. Production Decomposition of Domestically- and Foreign-owned Firms and Related Emissions

Source and destination of emissions \ Production activities		Domestic production in the host country	Final exports production in the host country	Simple intermediate exports production	Complex intermediate exports production
(Emissions) Production generated by Domestically-owned firms	Used in final production by domestically-owned firms	$\hat{E}_D L\hat{Y}_D^L$	$\hat{E}_D L\hat{Y}_D^E$	$\hat{E}_D LA^E L\hat{Y}_D^L$	$\hat{E}_D LA^E(B\hat{Y}_D - L\hat{Y}_D^L)$
	Used in final production by foreign-owned firms	$\hat{E}_D L\hat{Y}_F^L$	$\hat{E}_D L\hat{Y}_F^E$	$\hat{E}_D LA^E L\hat{Y}_F^L$	$\hat{E}_D LA^E(B\hat{Y}_F - L\hat{Y}_F^L)$
(Emissions) Production generated by Foreign-owned firms	Used in final production by domestically-owned firms	$\hat{E}_F L\hat{Y}_D^L$	$\hat{E}_F L\hat{Y}_D^E$	$\hat{E}_F LA^E L\hat{Y}_D^L$	$\hat{E}_F LA^E(B\hat{Y}_D - L\hat{Y}_D^L)$
	Used in final production by foreign-owned firms	$\hat{E}_F L\hat{Y}_F^L$	$\hat{E}_F L\hat{Y}_F^E$	$\hat{E}_F LA^E L\hat{Y}_F^L$	$\hat{E}_F LA^E(B\hat{Y}_F - L\hat{Y}_F^L)$

To provide a clearer picture of the production activities and related emissions, Table 1 presents how the production and the related emissions of a country sector can be decomposed according to different GVC routes and how different parts of these emissions form the six types of emissions: (1) pure domestic emissions (a type of pure self-responsibility) colored in gray, (2) traditional trade-related emissions colored in red, (3) trade-related GVC emission colored in orange, (4) Emissions by FDI-related GVC production for host country market (FDI-related domestic emissions in short)colored in blue; 5) Emissions by FDI-related GVC production for global market (FDI-related foreign emission in short) colored in yellow, as well as (6) both trade-and-FDI-related GVC emissions colored in green. In Table 1, the gray cell represents emissions that originate from and complete production by domestically-owned firms to meet domestic final demands, which are emissions embodied in pure domestic production activities. The red cell represents emissions that originate from and complete production by domestically-owned firms to meet foreign demands through final exports, which are emissions embodied in traditional trade-related non-GVC activities. The orange cells represent emissions that originate from and are exported as intermediates by domestically-owned firms, which are emissions embodied in trade-related GVC activities. The blue cells represent emissions that either originate from or complete production by MNEs to meet domestic final demands in host country, which are emissions embodied in FDI-related GVC activities for host country market. The yellow cells represent emissions that either originate from or complete production by MNEs to meet foreign final demands through final exports, which are emissions embodied in FDI-related activities for global markets. The green cells represent emissions that either originate from or are exported as intermediates by MNEs, which are emissions embodied in both trade-and FDI-related GVC activities.

The data used in this study are from two sources. First, we used a newly published time series AMNE-ICIO database constructed by the OECD that provides detailed transactions among 34 industries based on the ISIC Rev. 4 classification at the basic price in 60 economies (including the “rest of the world” as an economy) and between domestically- and foreign-owned firms in each industry. It further splits the OECD ICIO tables according to the ownership of firms from 2005 to 2016 based on firm-level information in the OECD AMNE database. Foreign-owned firms are defined as foreign affiliates that have at least 50 percent foreign ownership, and domestically-owned firms include domestic MNEs (domestically-owned firms with foreign affiliates) and domestically-owned firms that are not involved in international investment. Table 2 provides the layout of the OECD’s AMNE-ICIO table.

Table 2. The Layout of the OECD's AMNE-ICIO Table

Inputs \ Outputs		Intermediate Use							Final Demand				Total Output
		1		2		⋯	G		1	2	⋯	G	
Intermediate Inputs	1	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
		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
	2	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
		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
	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋱	⋮	⋮
	G	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
		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		$(X_D^1)'$	$(X_F^1)'$	$(X_D^2)'$	$(X_F^2)'$	⋯	$(X_D^g)'$	$(X_F^g)'$					

Notes: $\boldsymbol{Z}_{FD}^{12}$ is the N by N matrix, representing the exports of intermediate inputs produced by foreign-owned firms in country 1 used by country 2's domestically-owned firms. $\boldsymbol{Y}_F^{12}$ is the N by 1 vector representing the exports of final products produced by foreign-owned firms in country 1 used by country 2. $\mathbf{X}$ is the 2*GN by 1 column vector of output, and $\boldsymbol{V_a}$ is the 1 by 2*GN row vector of value added. For detailed information on the country or regional sector classification, see Appendixes 6 and 7. For a detailed explanation of the data, see Cadestin et al. (2018).

Second, the emissions data employed in this study are also from the OECD, which provides the CO_2 emissions of 60 countries and 34 sectors from 2005 to 2015. As these data do not provide CO_2 emissions according to firm types, we split each country-sector emissions by firm type based on two assumptions (Jiang et al., 2015; Zhang et al., 2020; Duan and Jiang, 2021). One assumption is that the carbon intensity is the same as the per unit of energy use at the country-sector level; that is, domestically-owned firms or MNEs in the same country-sector have the same CO_2 emissions per unit of energy consumption. The other assumption is that the amount of energy consumed is proportional to the sum of intermediates measured from primary energy sectors in the IO table. By assuming that more energy intermediates use generating more CO_2 emissions at the firm level (by firm ownership) in the same sector, we estimate the country-sector-firm-level emissions for 60 countries and 34 sectors from 2005 to 2015.

3. Results at the aggregated level

In this section, we present the major numerical results in three steps. First, we demonstrate the decomposition of emissions by Annex B country group (most are developed countries in the Kyoto Protocol and are also referred to in this paper as north countries) and non-Annex B country group (most are developing countries in the Kyoto Protocol and are also referred to in this paper as south countries) using the newly developed accounting framework and OECD AMEN-ICIO tables from 2005 to 2015. Second, we report inter-country/region emissions transfers at the bilateral level and focus on the South-North, US–China, Germany–China, and China–India trade pairs. Third, we present the results at the sector level and provide the decomposition results for eight different sectors in 10 major economies in 2015.

3.1 Emissions by different country groups

By applying this newly developed accounting framework that highlights the importance of FDI, we trace not only consumption- and production-based emissions and value added from 1995 to 2015 for both developed and developing countries, but also demonstrate how the international transfer of emissions occurs through various routes with different carbon intensities (such as emissions per US dollar of GDP created). Figure 2 depicts the production- and consumption-based emissions of developed and developing countries by different GVC routes. In 2015, self-responsibility-related emissions accounted for 76.9 percent and 75.7 percent of all production-based emissions of developed and developing countries, respectively, in which pure domestic and FDI-related domestic emissions accounted for 64.5 percent and 12.4 percent in developed countries and 69.9 percent and 5.8 percent in developing countries, respectively. The remaining 23.1 percent and 24.3 percent of production-based emissions in developed and developing countries should be shared. FDI-related foreign emissions, trade-related non-GVC emissions, trade-related GVC emissions, as well as trade-and-FDI-related emissions accounted for 2.5 percent, 5.2 percent, 9.7 percent, and 5.6 percent, respectively, in developed countries and 2.3 percent, 6.2 percent, 11.6 percent, and 4.1 percent, respectively in developing countries. GVC-related emissions, comprising FDI-related domestic emissions, FDI-related foreign emissions, trade-related GVC emissions, as well as trade-and-FDI-related emissions, accounted for 30.3 percent and 23.9 percent of all production-based emissions of developed and developing countries, respectively.

Production- and consumption-based CO_2 emissions of developed countries have both decreased over the past two decades. The production-based CO_2 emissions of developed countries increased slightly from 2005 to 2007 (peaking in 2007), decreased from 2007, and reached 10.1 Gt in 2015, which is less than their 2005 level of 11.5 Gt. The consumption-based emissions of developed countries have also decreased since 2007, reaching 11.2 Gt in 2015, which is also less than their 2005 level of 13.0 Gt. However, the trend of the developing countries was different. Both the production- and consumption-based CO_2 emissions of developing countries increased rapidly from 2005 to 2015. The production-based CO_2 emissions of developing countries increased from 12.4 Gt in 2005 to 18.7 Gt in 2015, with an increase of 51.1 percent. The consumption-based CO_2 emissions of developing countries increased even faster, from 10.9 Gt in 2005 to 17.6 Gt in 2015, an increase of 61.5 percent. The increase in emissions of developing countries largely exceeds the reduction in emissions of developed countries and has become the main driving force of the overall increase in global CO_2 emissions.

The facts become clearer when the structure of emissions routes is also considered. During this period, the decrease in developed countries' production-based CO_2 emissions was driven mainly by its reduction in domestic emissions, with a decrease of 16.9 percent. Trade-related non-GVC and trade-related GVC emissions also decreased by 2.1 percent and 8.3 percent, respectively, whereas FDI-related domestic emissions, FDI-related foreign emissions, and FDI-and-trade-related emissions increased slightly, by 1.9 percent, 3.4 percent, and 1.9 percent, respectively. The decrease in developed countries' consumption-based CO_2 emissions was driven by not only the 16.9 percent reduction in pure domestic emissions but also a 10.3 percent reduction in trade-related non-GVC emissions, a 1.2 percent reduction in FDI-related foreign emissions, an 18.1 percent reduction in trade-related GVC emissions, and a 7.5 percent reduction in FDI-and-trade-related emissions.

The details about developing countries present a different picture. During the same period, all six routes contributed to the increase in developing countries' production-based CO_2 emissions. The growth of pure domestic emissions in developing countries has been extremely rapid, with an increase of 65.3 percent, followed by FDI-related domestic and foreign emissions, with increases of 36.9 percent and 35.0 percent, respectively. Trade-related non-GVC and trade-related GVC emissions increased by 25.4 percent and 22.0 percent, respectively, and FDI-and-trade-related emissions have increased by 20.0 percent. The consumption-based CO_2 emissions of developing countries witnessed the largest increase. FDI-related foreign emissions, trade-related non-GVC emissions, trade-related GVC emissions, and FDI-and-trade-related emissions increased by 71.5 percent, 69.7 percent, 52.5 percent, and 49.0 percent, respectively. The GVCs structure of emissions highlights the role of developing countries in the global CO_2 emissions, which has already become too large to neglect. The huge amounts of FDI-related and FDI-and-trade-related emissions also demonstrate that production sharing across countries has changed the simple pattern of emissions and, to be successful, any mitigation target should consider these amounts of emissions.

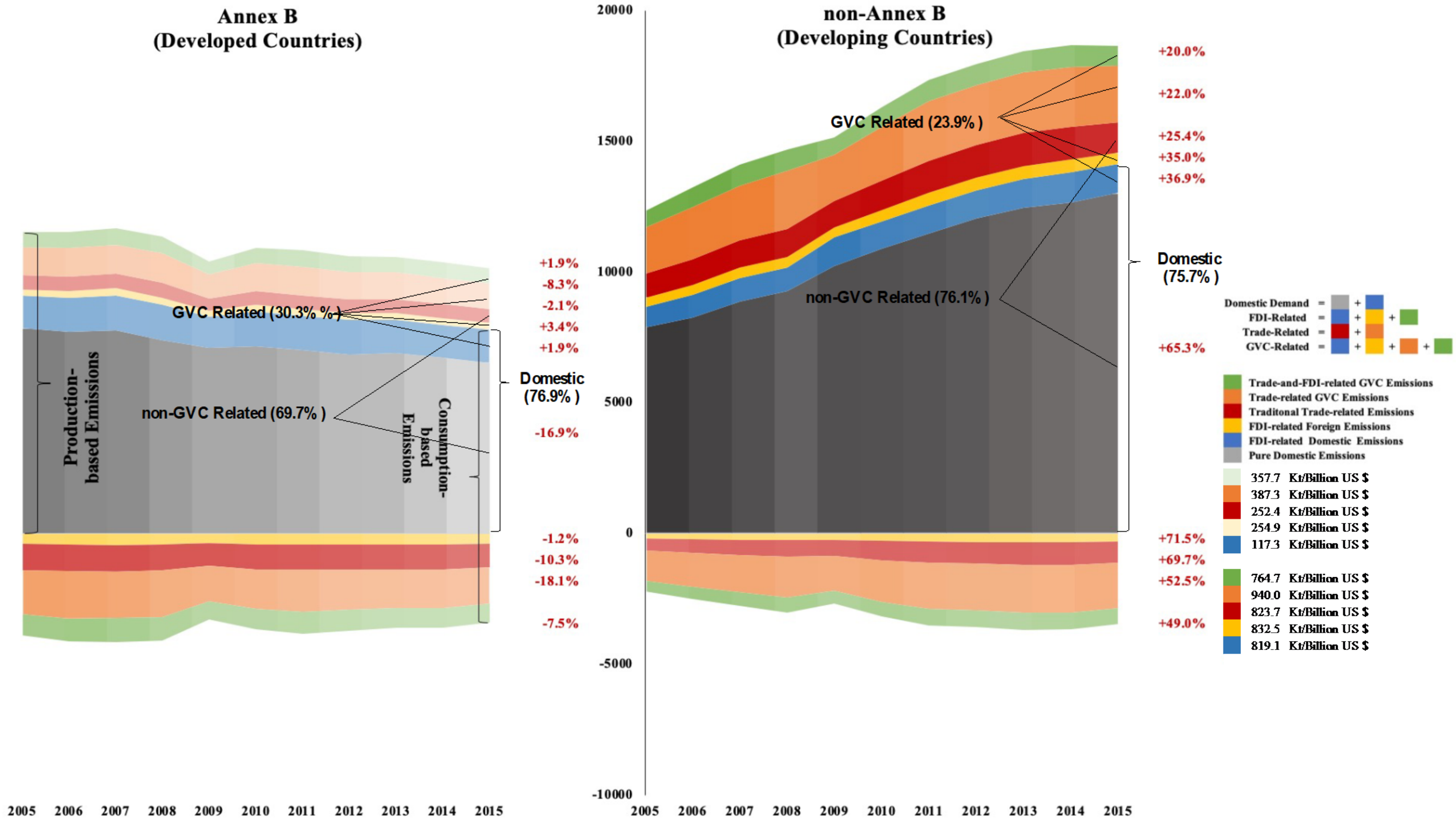

Figure 2. Emissions of Annex B vs Non-Annex B Country Groups from 2005 to 2015

By tracing both the emissions and the value added under this accounting framework, we can estimate the CO_2 intensities of each GVC route. Figure 2 also depicts the changes in CO_2 intensities of developed and developing countries from 2005 to 2015 at the 2015 constant price. The CO_2 intensity for pure domestic, FDI-related domestic, FDI-related foreign, trade-related non-GVC, trade-related GVC, and trade-and-FDI-related routes decreased from 714.8, 819.1, 829.8, 823.7, 940.0, and 758.2 Kt/Billion US$ to 615.6, 704.6, 703.0, 677.3, 841.1, and 658.0 Kt/Billion US$ in developing countries and from 286.3, 468.2, 340.4, 316.7, 536.0, and 458.3 Kt/Billion US$ to 220.0, 385.4, 254.9, 252.4, 387.3, and 357.7 Kt/Billion US$ in developed countries, respectively. During this period, the average CO_2 intensity of different routes of developed countries decreased by 21.7 percent, from 322.2 to 252.1 Kt/Billion US$, and that of developing countries decreased by 14.7 percent, from 759.7 to 647.7 Kt/Billion US$. Although the CO_2 intensity gap between the two country groups has been narrowed from 437.5 Kt/Billion US$ to 395.6 Kt/Billion US$, the percentage change of developed country group's intensity shows more rapid decline (21.7%) compared to the developing country group (14.7%) between 2005 and 2015. Moreover, the CO_2 intensity of developing countries in 2015 was still higher than that of developed countries in 2005. For detailed country-level results for Figure 2, refer to Table B1 in Appendix B.

3.2 Emissions Transfer along GVCs

3.2.1 South–North Emissions Transfer along GVCs

To provide a better understanding of how GVCs have restructured the emissions transfer between south and north countries, this study analyzes emissions transfers in the GVCs of south–south, south–north, north–north, and north–south trade. Figure 3 depicts the emissions transfer between the four pairs through each of the six routes in 2005 and 2015. Figure 3 presents several interesting facts. First, trade-related, FDI-related, and trade-and-FDI-related emissions account for over one-third of production-based emissions in both the north and south countries in 2015. Second, in 2015, about half of trade-related, FDI-related, and trade-and-FDI-related emissions on the production-side were within the south–south or north–north trade, and the remaining half was embodied in the south–north or north–south trade. Moreover, two-thirds of consumption-based trade-related, FDI-related, and trade-and-FDI-related emissions of the north countries come from the south–north trade, whereas one-third of that of the south countries come from the north–south trade. Third, by comparing the emissions transfer and value added of 2015 to the base year (2005), we also find that south–south emissions transfers through FDI-related

GVC activities experienced a rapid increase and are more carbon intensive than the value-added creation activities that were purely conducted domestically. Through FDIs, MNEs have played a significant role in the south countries in both generating emissions as energy users and transferring emissions as intermediate goods users in GVCs.

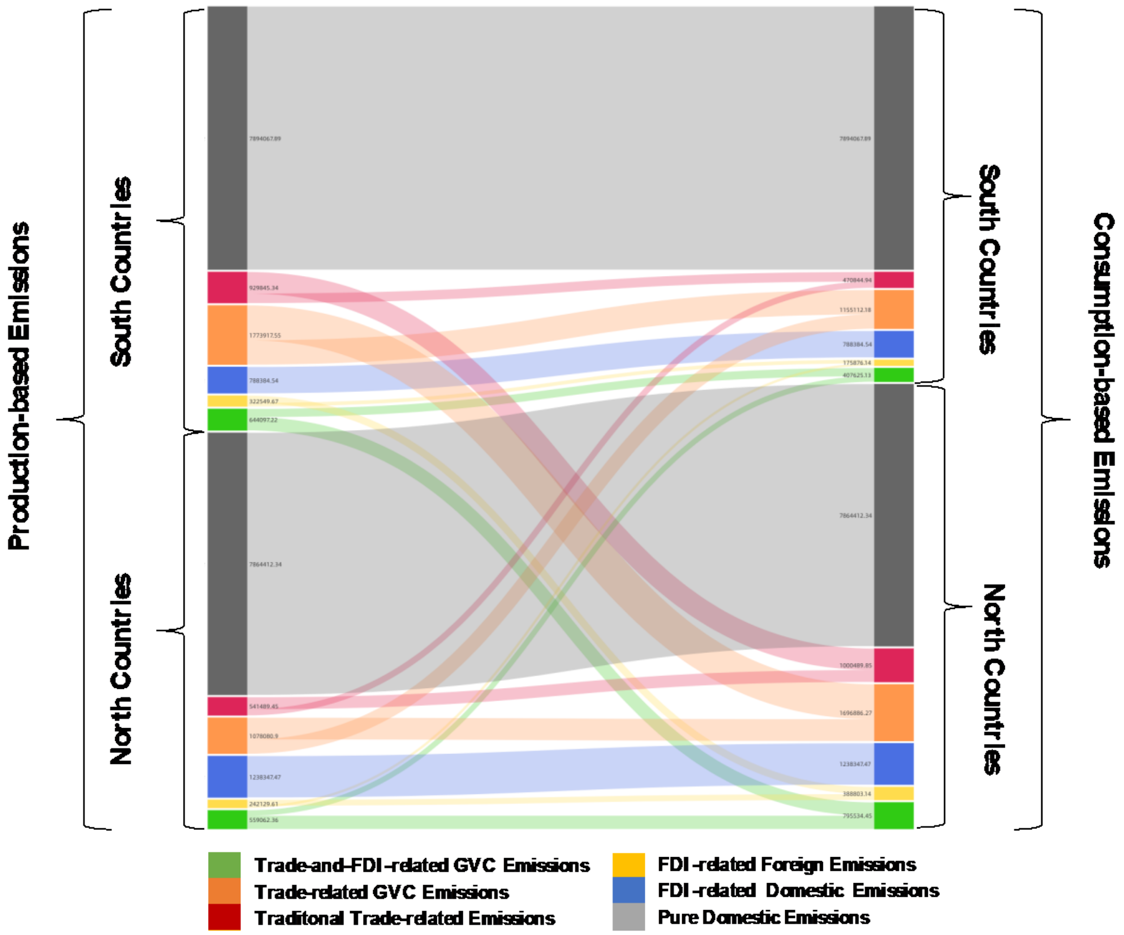

Figure 3a. Emissions Transfer between the South and North Countries in 2005

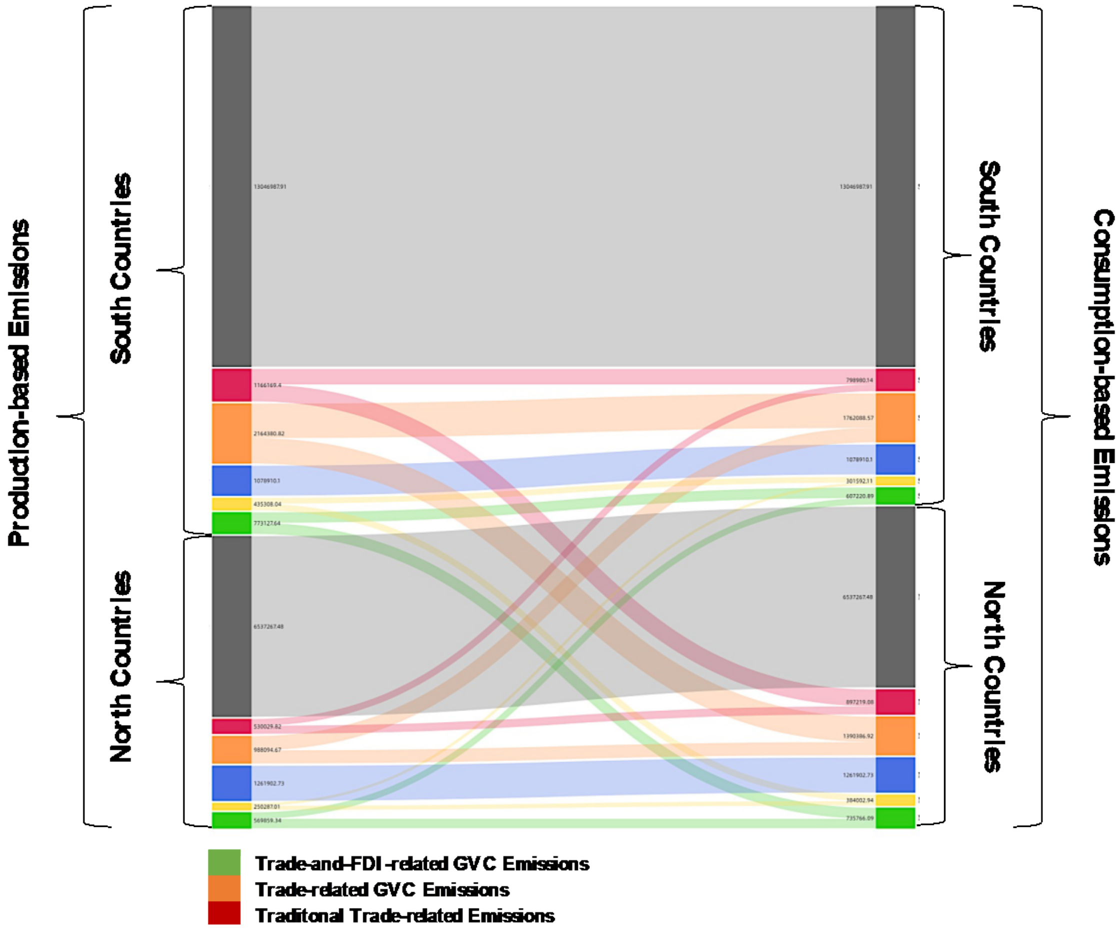

Figure 3b. Emissions Transfers between South and North Countries in 2015

3.2.2 Country-bilateral Emissions transfers along GVCs

As the comparison between developed and developing countries illustrates how the global emissions are driven by different GVCs routes, further decomposition of emissions to the bilateral level can provide more information on how the trade, FDI, and development stages formulate the interchange of emissions between countries. In this part, we focus on three trade pairs – US–China, Germany–China, and China–India –as they are not only three of the largest trade pairs worldwide, but also highly representative of their respective economic groups.

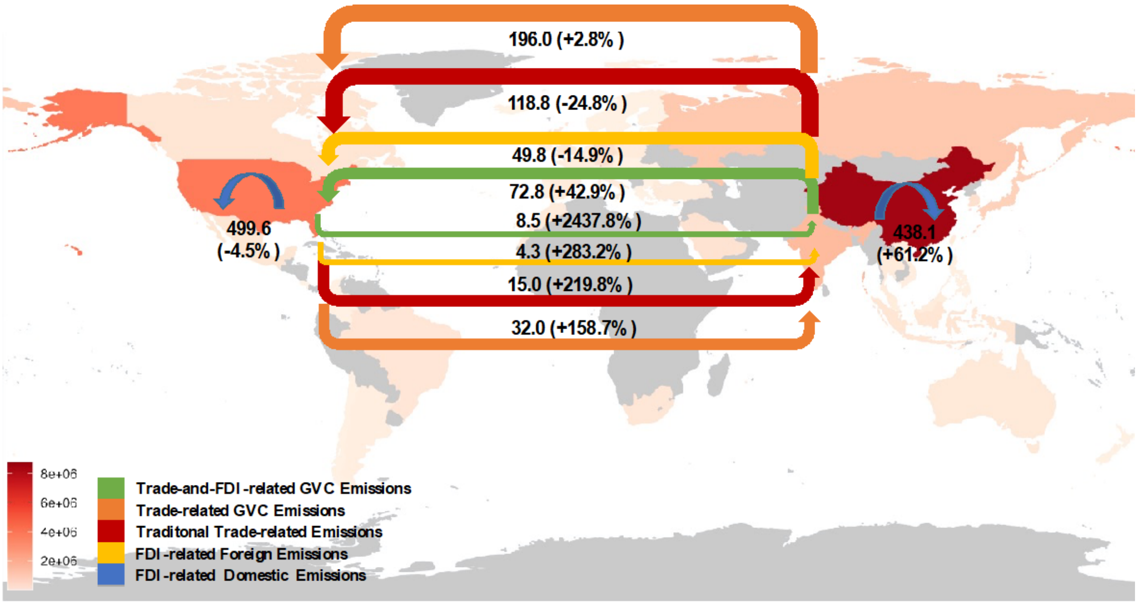

Figure 4. Bilateral Emissions in the US and China Trade in 2015 Compared with those of 2005 (Unit: Mt)

Note: The numbers along each arrow show the CO_2 emissions embodied in the corresponding GVC or non-GVC route in 2015. The percentages in parentheses are the relative increases from 2005 to 2015, and the signs in parentheses show the direction of changes.

Figure 4 depicts the emissions flows between the US and China in 2005 and 2015. The US and China are not only the largest trade pair in the world, but also the largest two CO_2 emitters. During this period, the territorial emissions of China induced by the US decreased slightly, whereas that of the US induced by China increased rapidly (although they were still less than those of its counterparts). In 2015, the territorial emissions of China induced by the US demand comprised the following four parts: 118.8 Mt of trade-related non-GVC emissions with a decrease of 24.8 percent since 2005, 196.0 Mt of trade-related GVC emissions with an increase of 2.8 percent, 49.8 Mt of FDI-related foreign emissions with a decrease of 14.9 percent, and 72.8 Mt of FDI-and-trade-related emissions with an increase of 42.9 percent. The territorial emissions of the US induced by China's demand are much smaller, but are accompanied by a sharp increase; only 15.0 Mt of trade-related non-GVC emissions with a rapid increase of 219.8 percent since 2005, 32.0 Mt of trade-related GVC emissions with an increase of 158.7 percent, 4.3 Mt of FDI-related foreign emissions with an increase of 283.2 percent, and 8.5 Mt of FDI-and-trade-related emissions with a drastic increase of 2437.8 percent. During this period, the US territorial emissions induced by China's demand have almost tripled, with the largest increase in trade-related non-GVC emissions and the highest growth rate being FDI-and-trade-related emissions.

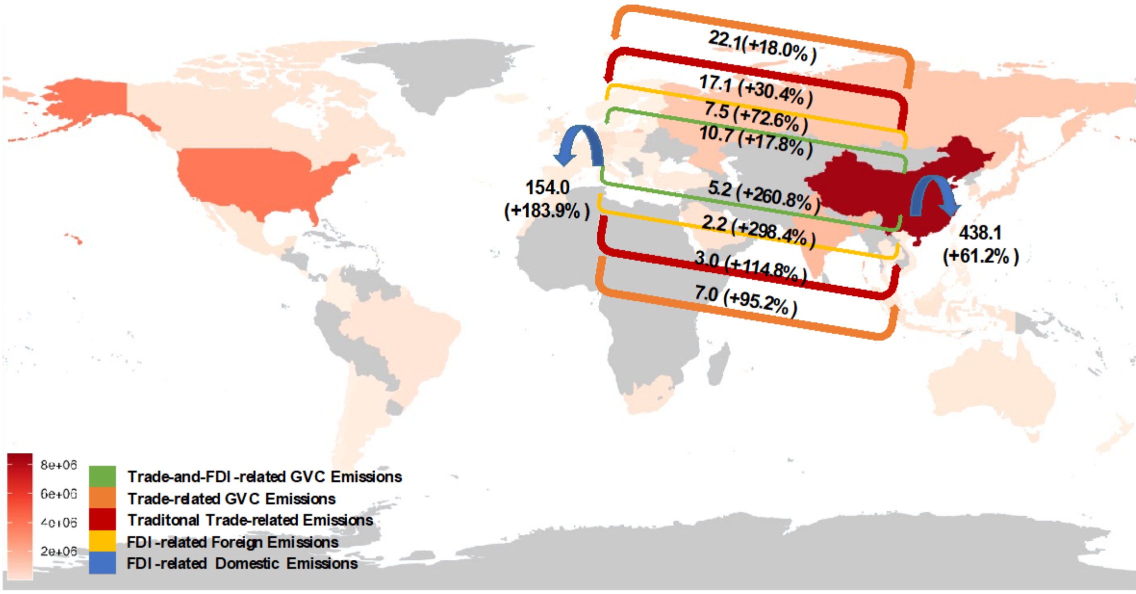

Figure 5. Bilateral Emissions in the Germany and China Trade in 2015 Compared with those of 2005 (Unit: Mt)

Figure 5 depicts the emissions flows between Germany and China in 2005 and 2015. The Germany–China trade pair was selected because these two countries are highly representative of Europe and developing economies, respectively. Unlike the US–China trade pair and possibly driven by the increasing trade volume between Germany and China, the territorial emissions of China induced by Germany increased slightly until 2015: 17.1 Mt of trade-related non-GVC emissions with an increase of 30.4 percent since 2005, 22.1 Mt of trade-related GVC emissions with an increase of 18.0 percent, 7.5 Mt of FDI-related foreign emissions with an increase of 72.6 percent, and 10.7 Mt of FDI-and-trade-related emissions with an increase of 17.8 percent. Germany's territorial emissions induced by China almost tripled from 2005 to 2015, including 3.0 Mt of trade-related non-GVC emissions with an increase of 114.8 percent, 7.0 Mt of trade-related GVC emissions with an increase of 95.2 percent, 2.2 Mt of FDI-related foreign emissions with an increase of 298.4 percent, and 5.2 Mt of FDI-and-trade-related emissions with an increase of 260.8 percent.

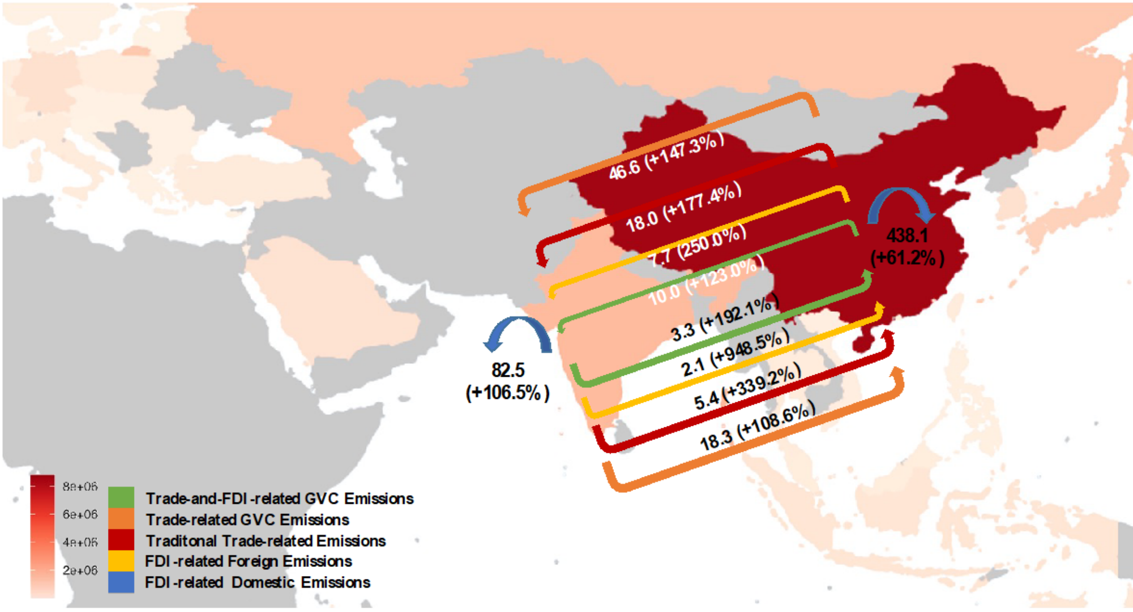

Figure 6. Bilateral Emissions in the India and China Trade in 2015 Compared with those of 2005 (Unit: Mt)

Figure 6 depicts the emissions flows between China and India in 2005 and 2015, which are two of the world's largest developing economies. The India–China trade pair was selected to represent the south–south trade. During this period, emissions through all routes between these two countries increased rapidly.

In 2015, the territorial emissions of China induced by India comprised 18.0 Mt of trade-related non-GVC emissions with an increase of 177.4 percent since 2005, 46.6 Mt of trade-related GVC emissions with an increase of 147.3 percent, 7.7 Mt of FDI-related foreign emissions with an increase of 250.0 percent, and 10.0 Mt of FDI-and-trade-related emissions with an increase of 123.0 percent. In 2015, the territorial emissions of India induced by China's demand comprised 5.4 Mt of trade-related non-GVC emissions with an increase of 339.2 percent since 2005, 18.3 Mt of trade-related GVC emissions with an increase of 108.6 percent, 2.1 Mt of FDI-related foreign emissions with an increase of 948.5 percent, and 3.3 Mt of FDI-and-trade-related emissions with an increase of 192.1 percent. From 2005 to 2015, emissions embodied in the south–south trade increased much faster than that in the south–north trade. Emissions in US and German trade induced by China's demand increased, which is consistent with the increase in emissions imported from developed countries by developing economies depicted in Figure 3. The emissions embodied in GVCs in Indian and Chinese trade increased for all routes. The structure of different GVCs routes indicates that FDI-related emissions and FDI-and-trade-related emissions increased rapidly, which highlights the roles and responsibilities of MNEs in regulating the world's CO_2 emissions.

3.3 Sector level emissions along GVCs

As different sectors can be very different due to production technologies, countries' endowments, trade and FDI characteristics, as well as many other aspects, we cluster these sectors according to the GVC patterns. The sectors are clustered into four or five groups according to the distribution of emissions in six GVC routes, which are provided in the Appendix as Figure C1. We find that there is substantial heterogeneity between the sectors in terms of the emissions volume, the structure of GVCs routes, and the host countries' production patterns. We further reveal the detailed results for eight different sectors in 10 major economies for 2015. The eight sectors are food, textile, motor vehicles, wholesale and retail, petroleum refining, ICT, telecommunications, as well as IT and information services. The 10 countries are China, India, Japan, the US, Canada, Germany, Great Britain, France, Russia, and Brazil, which are the top 10 CO_2 emitters in the world.

Figure 7 depicts the production-based emissions according to six types of GVCs routes of several sectors. Regarding the food sector, which is highly domestic and less fragmented, China, the US, and India are the largest host countries by volume of emissions. Most of the emissions in the food sector are domestic because the emissions embodied in food are usually produced and consumed in the same country. For instance, the emissions of the food sector in China comprise 91.0 Mt of pure domestic CO_2 emissions, 3.6 Mt of trade-related non-GVC emissions, 3.4 Mt of trade-related GVC emissions, 9.0 Mt of FDI-related domestic demand emissions, 0.9 Mt of foreign demand emissions, and 1.0 Mt of FDI-and-trade-related emissions.

The petroleum refining sector has some of the highest CO_2 emissions. Russia emits the most CO_2 emissions among the 10 countries on our list, followed by China, the US, India, and Brazil. Since Russia is the largest exporter of energy resources, a large part of its petroleum refining emissions is trade-related, which even exceeds its pure domestic emission. The emissions of the petroleum refining sector in Russia comprise 78.1 Mt of pure domestic emissions, 39.3 Mt of trade-related non-GVC emissions, 79.9 Mt of trade-related GVC emissions, 2.8 Mt of FDI-related domestic demand emissions, 1.7 Mt of foreign demand emissions, and 19.3 Mt of FDI-and-trade-related emissions. China, the second-largest emitter, has a larger share of emissions for its domestic demands. Moreover, Canada, as one of the largest energy providers, has a high share of FDI-related emissions emitted by the foreign affiliates of multinational energy companies headquartered in other countries.

Regarding the textile sector, China is not only the largest provider of textile and clothing products, but also the largest CO_2 emitter. Nearly half of the production-based emissions in the textile sector of China are generated to meet domestic demands, which is 24.2 Mt of pure domestic emissions and 1.5 Mt of FDI-related domestic demand emissions. The rest are embodied in products exported to foreign countries, including 13.9 Mt of trade-related non-GVC emissions, 9.6 Mt of trade-related GVC emissions, 1.5 Mt of FDI-related foreign demand emissions, and 2.1 Mt of FDI-and-trade-related emissions. Most of these emissions embodied in exports are trade-related, produced by Chinese enterprises to meet foreign demands.

The ICT sector, which is classified as high-technology digital manufacturing, has more MNEs and is more deeply embedded in the GVC than other traditional industries. Although China produces the largest CO_2 emissions in the ICT sector, only one-third of these emissions are for its domestic demands, the rest are induced by foreign demands. Over one-third of China's ICT emissions are related to MNEs because China has attracted many foreign affiliates of MNEs with its market size and low labor costs. Specifically, the emissions of the ICT sector in China comprise 10.7 Mt of pure domestic emissions, 4.7 Mt of trade-related non-GVC emissions, 5.4 Mt of trade-related GVC emissions, 2.9 Mt of FDI-related domestic demand emissions, 5.2 Mt of foreign demand emissions, and 6.0 Mt of FDI-and-trade-related emissions. The share of FDI-related or FDI-and-trade-related emissions is much larger in the ICT sector than in the food, textile, and many other sectors, due to the emergence of large MNEs, including IBM, Apple, and Samsung.

Regarding the motor vehicle sector, India, China, and the US are the top emitters. All 10 countries listed in Figure 7 have high levels of FDI-related emissions in this sector. FDI-related emissions, including domestic and foreign demands routes, account for 25.8 percent of the total motor vehicle emissions in China, 33.7 percent in India, 40.2 percent in the US, 62.4 percent in Canada, 66.6 percent in the UK, 36.5 percent in Russia, and 73.5 percent in Brazil. This can be explained by the extensive existence of multinational motor vehicle enterprises in all countries, such as Tesla, Volkswagen, and Toyota. This can also be explained by the complex techniques and know-how embodied in motor vehicles, which makes it more difficult to develop the motor vehicles sector in developing countries. Thus, it is a sector with a high concentration of large MNEs. For example, in India, the total emissions of the motor vehicles sector comprise 19.1 Mt of pure domestic emissions, 1.8 Mt of trade-related non-GVC emissions, 0.6 Mt of trade-related GVC emissions, 9.9 Mt of FDI-related domestic demand emissions, 1.5 Mt of foreign demand emissions, and 1.0 Mt of FDI-and-trade-related emissions, with nearly two-fifths of its motor sector's emissions being FDI-related or FDI-and-trade-related.

Regarding the telecommunications and IT services sectors, the US is the largest emitter in these two sectors, followed by China, India, and Japan. As the service sectors are usually less tradable than the manufacturing sectors, a higher share of emissions is usually a result of the countries' own domestic demands. By comparing the ICT sector and these two sectors, we find the differences between the digital manufacturing and digital service sectors.

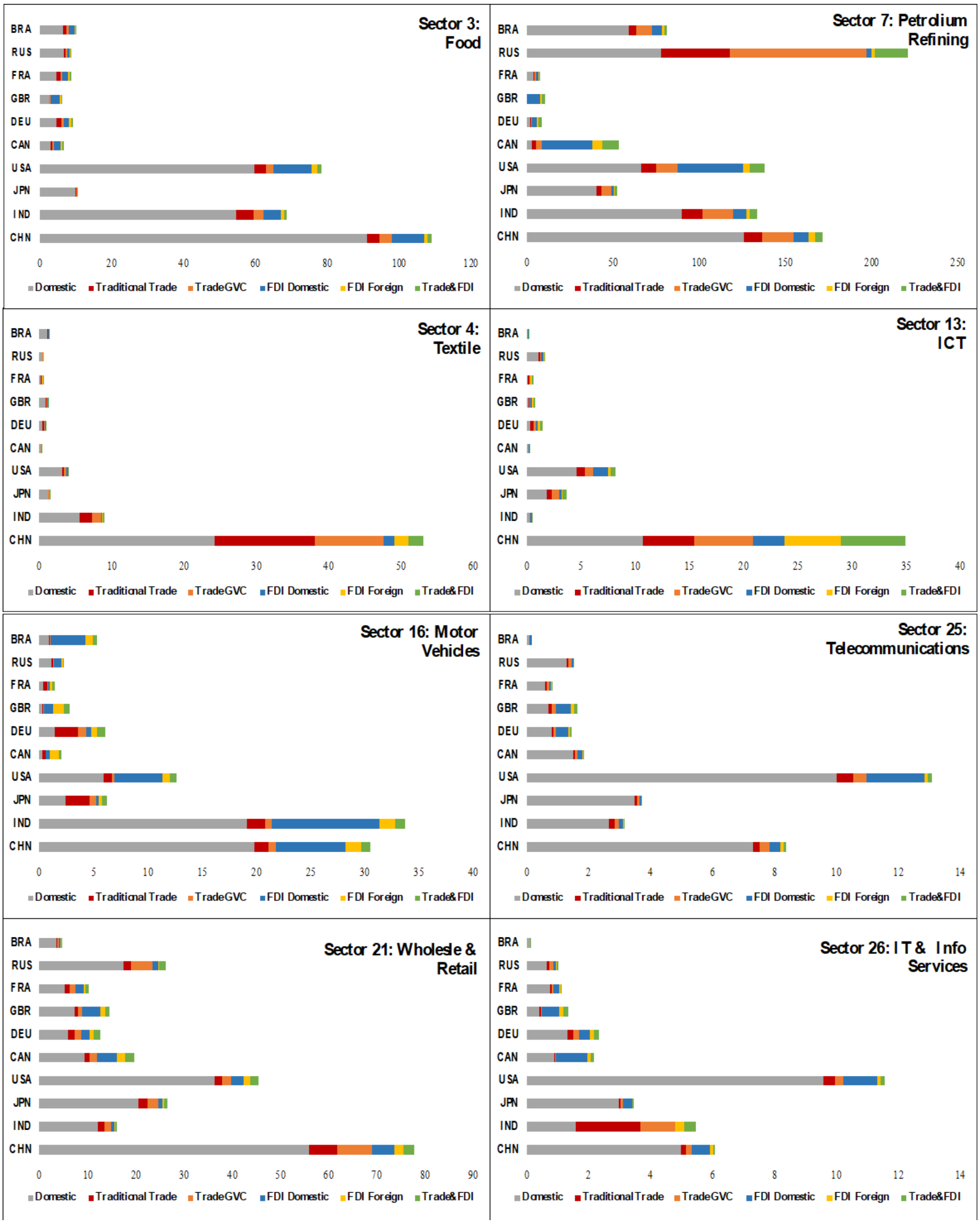

Figure 7. Sector Level Emissions along GVCs in 2015 (Unit: Mt)

4. Conclusion

By applying a suitable accounting framework to the OECD AMNE-ICIO database, this study traces both emissions and value added by firm ownership at each stage of the GVC at the bilateral country-sector level. Our empirical results can contribute to several important and deep discussions about the response to climate change in the era of GVCs by explicitly considering MNEs' activities.

First, our empirical results demonstrate that CO_2 emissions generated through pure domestic value chains without any production sharing (a type of pure self-responsibility) account for about 64.5 percent and 69.9 percent of the total CO_2 emissions of developed and developing countries, respectively. Although a consensus has been reached on "Common but Differentiated Responsibilities" (CBDR) in the international community, there are still many challenges to the effective implementation of CBDR, especially concerning the treatment of historical responsibility for climate change. The level of concern for the historical accumulation of CO_2 emissions generated in the era of Western countries' industrialization may decrease because of the rapidly increasing level of self-responsibility-based emissions in developing countries. Using the GVC-based accounting framework proposed in this study, it may be easier to achieve a consensus on controlling self-responsibility-based emissions rather than reallocate shared responsibilities through international negotiation. More importantly, given the urgency to limit global warming to 1.5 degrees Celsius – and given that most developing countries have no absolute emissions reduction targets, coupled with the relatively weak environmental regulations – helping developing countries set appropriate targets for emissions peak in terms of the current pure self-responsibility-based emissions estimates can be a constructive way to curb the rapid increase in global carbon emissions in the post-Paris Agreement era.

Second, our empirical results reveal that, in 2015, GVC-related emissions, comprising trade-related GVC emissions, FDI-related domestic emissions, FDI-related foreign emissions, and trade-and-FDI-related emissions accounted for 23.9 percent and 30.3 percent of the total production-based emissions in developing and developed countries, respectively. All emissions related to FDI (comprising FDI-related domestic emissions, FDI-related foreign emissions, and trade-and-FDI-related GVC emissions) accounted for 58.1 percent of the world's GVCs emissions and 15.2 percent of the world's total emissions, in which emissions related to FDI for foreign demands (comprising FDI-related foreign emissions and trade-and-FDI-related GVC emissions) accounted for 39.2 percent of the world's GVCs emissions for foreign demands. About half of trade-related, FDI-related, and trade-and-FDI-related emissions on the production side are within the south–south or north–north trade, and the remaining half are embodied in the south–north or north–south trade. South–south emissions transfers through FDI-related GVC activities experienced a rapid increase and are more carbon-intensive than those in value-added creation activities that were purely conducted domestically. Moreover, MNEs play a significant role through FDIs in the south countries in terms of both generating emissions as energy users and transferring emissions as intermediate goods users in GVCs. All these findings provide new insights when considering the responsibility of MNEs in the context of both "pollution haven" and "race to the bottom" hypotheses.

Regarding emissions that are not self-responsibility based, our new GVC-based accounting framework may provide a useful basis for future negotiation, which can also help policymakers rethink how to deal with the so-called "carbon leakage" that happens through international trade and FDI channels in the GVCs. For example, carbon border taxes have been considered a quick and easy way to increase emitting costs globally. However, we suggest that all taxes should be imposed on the real beneficiaries of emissions, which requires GVC-based identification of the whole carbon footprint, not only just through trade, but also through FDI routes by firm ownership. These can help build more reasonable policy packages for better governance of global emissions reduction in the trade–investment–climate change nexus.

Our empirical results also demonstrate that there is substantial difference in the patterns in CO_2 emissions generation, transfer, and absorption in the GVCs by firm ownership. All these findings help us to clearly understand who creates emissions for whom and from which route. These findings can be used to monitor the difference between the National Determined Contributions nominated (or achieved) by countries to achieve their Paris Agreement target and their responsibility proposed in the paper, which will help more countries recognize how far their current efforts are from achieving their goals. Another possible policy application involves developing climate funds (collecting revenue from GVC responsibility-share-based carbon taxes or tariffs) that can be used to support not only renewable energy projects in developing countries, but also innovations that reduce the cost of capturing and storing carbon.

In summary, it is very important to fairly and efficiently make substantial increases to charges levied for carbon emissions by both MNEs and domestically-owned producers and consumers at all stages of the GVCs. This is because unless some of the largest emitting countries or regions, such as the US, China, and the EU achieve consensus, no scheme can raise sufficient funds to reduce global carbon emissions by the required amount.

This study is subject to several limitations. The first is that it only covers the period from 2005 to 2015 due to the availability of the CO2 emission data in OECD database. Another limitation is that this study assumed the same CO_2 emissions per unit US$ of energy used for domestically-owned firms and foreign firms within each country-sector, which might not fully capture the technical difference in energy use and the difference of energy price each type firms faced at the same country/sector .

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Appendix

Appendix A. FDI-related Emissions and Corresponding Shares

In Table A1, we present FDI-related emissions and shares in world emissions. Panel A reports the results for FDI-related GVC emissions. In Columns 1–3, we calculate all FDI-related GVC emissions, comprising FDI-related domestic, FDI-related foreign, as well as trade-and-FDI-related emissions for developed countries, developing countries, and the world. In Columns 4–6, we calculate all GVC-related emissions, comprising FDI-related domestic, FDI-related foreign, trade-and-FDI-related emissions, as well as trade-related GVC emissions for developed countries, developing countries, and the world. The share of all FDI-related GVC emissions in all GVC emissions is reported in Columns 7–9. Panel B reports the results for FDI-related GVC emissions that cross countries; that is, for foreign demands. Similarly, Columns 1–3 report the amount of FDI-related cross-country emissions; Columns 4–6 report the amount of GVC-related cross-country emissions, and columns 7–9 report the corresponding shares.

Table A1. FDI-related Emissions and Shares

Panel A	FDI related GVC emissions = FDI-D + FDI-F + Trade&FDI			GVC emissions = FDI-D + FDI-F + Trade&FDI + Trade-GVC			FDI related GVC emissions in GVC emissions			World's total emissions	
	developed	developing	world (F1)	developed	developing	world (G1)	developed	developing	F1/G1	T	F1/T
2005	2039.5	1755.0	3794.6	3117.62	3528.95	6646.6	65.4%	49.7%	57.1%	23876.4	15.9%
2006	2148.6	1986.5	4135.0	3241.80	3979.40	7221.2	66.3%	49.9%	57.3%	24755.4	16.7%
2007	2264.2	2074.0	4338.2	3362.59	4158.05	7520.6	67.3%	49.9%	57.7%	25784.9	16.8%
2008	2286.3	2141.6	4427.9	3416.28	4366.81	7783.1	66.9%	49.0%	56.9%	26046.1	17.0%
2009	1912.4	2128.2	4040.6	2836.92	3896.45	6733.4	67.4%	54.6%	60.0%	25572.3	15.8%
2010	2168.8	2227.8	4396.6	3228.17	4282.33	7510.5	67.2%	52.0%	58.5%	27252.3	16.1%
2011	2182.0	2396.0	4578.0	3283.52	4678.56	7962.1	66.5%	51.2%	57.5%	28207.4	16.2%
2012	2185.5	2355.8	4541.3	3223.49	4649.33	7872.8	67.8%	50.7%	57.7%	28570.5	15.9%
2013	2118.1	2412.6	4530.7	3136.26	4712.33	7848.6	67.5%	51.2%	57.7%	29027.0	15.6%
2014	2107.0	2455.0	4562.0	3115.34	4746.24	7861.6	67.6%	51.7%	58.0%	29065.8	15.7%
2015	2082.0	2287.3	4369.4	3070.14	4451.73	7521.9	67.8%	51.4%	58.1%	28802.3	15.2%
2005-2015	23494.4	24219.8	47714.2	35032.1	47450.2	82482.3	67.1%	51.0%	57.8%	296960.4	16.1%
Panel B	FDI related emissions cross countries = FDI-F + Trade&FDI			GVC emissions cross countries = FDI-F + Trade&FDI + Trade-GVC			FDI related GVC emissions in GVC emissions (cross countries)			World's total emissions	
	developed	developing	world (F2)	developed	developing	world (G2)	developed	developing	F2/G2	T	F2/T
2005	801.19	966.65	1767.8	1879.27	2740.56	4619.8	42.6%	35.3%	38.3%	23876.4	7.4%
2006	850.05	1122.88	1972.9	1943.29	3115.81	5059.1	43.7%	36.0%	39.0%	24755.4	8.0%
2007	916.27	1200.61	2116.9	2014.66	3284.68	5299.3	45.5%	36.6%	39.9%	25784.9	8.2%
2008	922.04	1220.04	2142.1	2052.05	3445.25	5497.3	44.9%	35.4%	39.0%	26046.1	8.2%
2009	740.77	1046.98	1787.7	1665.25	2815.24	4480.5	44.5%	37.2%	39.9%	25572.3	7.0%
2010	847.78	1196.96	2044.7	1907.19	3251.44	5158.6	44.5%	36.8%	39.6%	27252.3	7.5%
2011	895.51	1312.75	2208.3	1997.00	3595.33	5592.3	44.8%	36.5%	39.5%	28207.4	7.8%
2012	867.94	1300.18	2168.1	1905.92	3593.73	5499.7	45.5%	36.2%	39.4%	28570.5	7.6%
2013	862.00	1303.54	2165.5	1880.17	3603.28	5483.4	45.8%	36.2%	39.5%	29027.0	7.5%
2014	859.56	1318.45	2178.0	1867.92	3609.71	5477.6	46.0%	36.5%	39.8%	29065.8	7.5%
2015	820.15	1208.44	2028.6	1808.24	3372.82	5181.1	45.4%	35.8%	39.2%	28802.3	7.0%
2005-2015	9383.3	13197.5	22580.8	20921.0	36427.9	57348.8	44.9%	36.2%	39.4%	296960.4	7.6%

Appendix B. Emissions of Top 10 Countries and the Rest of the World in 2015

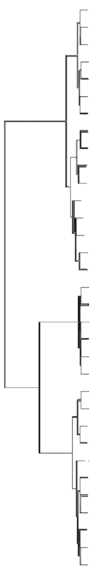
Table B1 presents the emissions of the top 10 countries and the rest of the world in 2015. Panel A reports their production-based CO_2 emissions through six GVC routes: (1) domestic, (2) trade-related non-GVC, (3) trade-related GVC, (4) FDI-related domestic, (5) FDI-related foreign, and (6) trade-and-FDI related. Panel B reports their consumption-based CO_2 emissions through the six GVC routes. We also report each country's share in the world on the production and consumption sides.

Table B1. Emissions of Top 10 Countries and the Rest of the World in 2015

	Country	Domestic	Trade-nonGVC	Trade-GVC	FDI-Domestic	FDI-Foreign	Trade&FDI	Share in Global Production-based CO2
Panel A: Producion-based								
1	CHN	6407 (73%)	521 (6%)	905 (10%)	438 (5%)	223 (3%)	277 (3%)	8772 (30%)
2	USA	3252 (77%)	148 (4%)	184 (4%)	500 (12%)	46 (1%)	83 (2%)	4213 (15%)
3	IND	1486 (78%)	120 (6%)	156 (8%)	83 (4%)	32 (2%)	40 (2%)	1916 (7%)
4	RUS	847 (61%)	98 (7%)	302 (22%)	44 (3%)	10 (1%)	79 (6%)	1380 (5%)
5	JPN	858 (79%)	56 (5%)	100 (9%)	31 (3%)	6 (1%)	29 (3%)	1080 (4%)
6	DEU	244 (41%)	39 (7%)	67 (11%)	154 (26%)	30 (5%)	66 (11%)	601 (2%)
7	KOR	341 (59%)	61 (11%)	120 (21%)	13 (2%)	8 (1%)	33 (6%)	577 (2%)
8	SAU	419 (79%)	22 (4%)	66 (13%)	9 (2%)	1 (0%)	12 (2%)	529 (2%)
9	CAN	215 (46%)	21 (4%)	57 (12%)	90 (19%)	26 (5%)	56 (12%)	464 (2%)
10	IDN	312 (72%)	23 (5%)	46 (11%)	29 (7%)	5 (1%)	18 (4%)	432 (2%)
11	ROW	5203 (59%)	587 (7%)	1149 (13%)	950 (11%)	298 (3%)	650 (7%)	8838 (31%)
Panel B: Consumption-based								
	Country	Domestic	Trade-nonGVC	Trade-GVC	FDI-Domestic	FDI-Foreign	Trade&FDI	Share in Global Consumption-based CO2
1	CHN	6407 (85%)	100 (1%)	433 (6%)	438 (6%)	36 (0%)	132 (2%)	7546 (26%)
2	USA	3252 (66%)	313 (6%)	493 (10%)	500 (10%)	139 (3%)	256 (5%)	4953 (17%)
3	IND	1486 (82%)	40 (2%)	151 (8%)	83 (5%)	14 (1%)	46 (3%)	1819 (6%)
4	RUS	847 (85%)	28 (3%)	50 (5%)	44 (4%)	10 (1%)	16 (2%)	995 (3%)
5	JPN	858 (69%)	84 (7%)	188 (15%)	31 (3%)	35 (3%)	49 (4%)	1245 (4%)
6	DEU	244 (35%)	82 (12%)	105 (15%)	154 (22%)	33 (5%)	72 (10%)	689 (2%)
7	KOR	341 (64%)	31 (6%)	111 (21%)	13 (2%)	10 (2%)	24 (5%)	529 (2%)
8	SAU	419 (76%)	46 (8%)	48 (9%)	9 (2%)	15 (3%)	15 (3%)	553 (2%)
9	CAN	215 (46%)	47 (10%)	59 (13%)	90 (19%)	20 (4%)	35 (7%)	466 (2%)
10	IDN	312 (70%)	21 (5%)	58 (13%)	29 (6%)	8 (2%)	17 (4%)	445 (2%)
11	ROW	5203 (54%)	904 (9%)	1456 (15%)	950 (10%)	366 (4%)	681 (7%)	9561 (33%)

Appendix C. Cluster of Sectors

Figure C1 clusters the sectors according to their GVC patterns. The clustering process is conducted by employing hierarchical cluster analysis and using the squared Euclidean distances between cluster means as the measure of dissimilarities. Initially, each sector is assigned to its cluster. The algorithm then proceeds iteratively at each stage to join the two most similar clusters and continues until there is just a single cluster. At each stage, the distances between the clusters are recomputed using the updated formula and Ward's minimum variance method. This method aims to find compact and spherical clusters. Figure C1 shows that the sectors can be clustered into four or five groups, and the sectors within each cluster are similar.



			Domestic	Trade-nonGVC	Trade-GVC	FDI-Domestic	FDI-Foreign	Trade&FDI
11	C24	Basic metals	55%	6%	20%	6%	3%	9%
7	C19	Coke and refined petroleum products	55%	9%	17%	10%	2%	6%
12	C25	Fabricated metal products	56%	9%	16%	8%	4%	8%
6	C17T18	Paper products and printing	59%	6%	14%	10%	3%	7%
9	C22	Rubber and plastic products	60%	7%	15%	8%	3%	7%
5	C16	Wood and products of wood and cork	63%	6%	18%	6%	2%	5%
22	H	Transportation and storage	61%	10%	14%	5%	4%	6%
15	C28	Machinery and equipment, nec	54%	13%	9%	9%	7%	7%
18	C31T33	Other manufacturing; repair and installation of machinery and equipment	55%	15%	6%	10%	9%	5%
4	C13T15	Textiles, wearing apparel, leather and related products	51%	23%	16%	3%	3%	4%
17	C30	Other transport equipment	51%	22%	8%	8%	6%	5%
16	C29	Motor vehicles, trailers and semi-trailers	44%	10%	4%	25%	11%	8%
2	B	Mining and extraction of energy producing products	45%	4%	29%	5%	2%	15%
13	C26	Computer, electronic and optical products	34%	13%	16%	9%	11%	16%
8	C20T21	Chemicals and pharmaceutical products	48%	7%	16%	14%	4%	10%
14	C27	Electrical equipment	49%	12%	14%	8%	6%	10%
30	O	Public admin. and defence; compulsory social security	99%	0%	0%	0%	0%	0%
31	P	Education	97%	2%	1%	1%	0%	0%
28	L	Real estate activities	93%	2%	2%	3%	1%	0%
33	RTS	Arts, entertainment, recreation and other service activities	92%	3%	2%	2%	0%	0%
20	F	Construction	95%	0%	1%	3%	0%	0%
32	Q	Human health and social work	94%	1%	2%	2%	0%	0%
21	G	Wholesale and retail trade; repair of motor vehicles	66%	7%	10%	8%	3%	5%
29	MTN	Other business sector services	67%	6%	10%	10%	2%	5%
26	J62T63	IT and other information services	62%	8%	6%	14%	4%	5%
27	K	Financial and insurance activities	65%	4%	7%	17%	2%	4%
23	I	Accommodation and food services	83%	9%	2%	3%	2%	1%
24	J58T60	Publishing, audiovisual and broadcasting activities	73%	5%	4%	15%	2%	2%
3	C10T12	Food products, beverages and tobacco	73%	8%	5%	10%	2%	2%
25	J61	Telecommunications	76%	5%	5%	11%	2%	2%
1	A	Agriculture, forestry and fishing	77%	8%	9%	3%	1%	2%
10	C23	Other non-metallic mineral products	73%	3%	11%	7%	2%	4%
19	DTE	Electricity, gas, water supply, sewerage, waste and remediation services	74%	4%	8%	9%	2%	3%

Figure C1. Cluster of Sectors According to GVC Patterns