Tracing Greenhouse Gas Emissions in Global Value Chains*

Bo MENG, Glen PETERS, and Zhi WANG

Abstract

This paper integrates two lines of research into a unified conceptual framework: trade in global value chains and embodied emissions. This allows both value added and emissions to be systematically traced at the country, sector, and bilateral levels through various routes in global production networks. By combining value-added and emissions accounting in a consistent way, the potential environmental cost (amount of emissions per unit of value added) along global value chains can be estimated from different perspectives (production, consumption, and trade). This helps clearly distinguish emissions of self and shared responsibilities between producers and consumers located in different territories. Using this unified accounting method, we trace CO_2 emissions in global production and trade networks among 41 economies in 35 sectors from 1995 to 2009 based on the World Input–Output Database, and show how they help us to better understand the impact of cross-country production sharing on the environment. .

Key Words: trade in value-added; embodied emissions; global value chains; environmental analysis; input–output analysis; international trade; carbon intensity

JEL Number: E01, E16, F1, F14, F18, Q5, Q54, Q56

* Meng (Institute of Developing Economies, JETRO, Japan); Peters (Center for International Climate and Environmental Research – Oslo (CICERO), Norway); and Wang (US International Trade Commission, Washington, D.C.). The views in the paper are those of the authors and may not reflect the views of the USITC and its Commissioners or any other organization that the authors are affiliated with. We thank Prof. Jinjun Xue (Nagoya University, Japan) and Dr. Kunfu Zhu (Chinese Academy of Sciences) for discussions related to this work and IDE-JETRO's peer reviewer, Dr. Masami Ishida for his comments on an earlier version of the draft. We are grateful for the financial support from CIDEG, Tsinghua University.

Tracing Greenhouse Gas Emissions in Global Value Chains

1. Introduction

The rise of global value chains (GVCs) during the last two decades has significantly changed the nature and structure of international trade, with many new implications for policy making (Baldwin, 2012; Timmer et al. 2013). Studies on GVCs have covered a variety of topics such as vertical specialization (Hummel et al. 2001), trade in tasks (Grossman and Rossi-Hansberg 2008; Baldwin and Robert-Nicoud 2014), magnification of trade cost from multi-stage production (Yi 2010), value chain organization (Antras and Chor 2013) as well as the measurement of the creation and distribution of employment and income in GVCs (OECD et al. 2013; Timmer et al. 2014b; Ferrarini and Hummels 2014). In recent years, however, many scholars have turned their attention to the interaction of GVCs and environmental policies (Hoekstra and Wiedmann 2014). A large body of literature has developed to assess "consumption-based accounting" of historical emissions (Tukker and Dietzenbacher 2013). It adjusts the standard territory-based accounts of emissions by removing the emissions associated with exports and adding the emissions associated with imports (Peters and Hertwich 2008). Most early studies focused on climate policy, where it was found that developed nations collectively have higher consumption-based emissions than territory-based emissions, meaning that they are net importers of emissions and thereby benefit from environmentally intensive production abroad (Davis and Caldeira 2010; Peters et al. 2011; Arto and Dietzenbacher 2014). The same conclusions have been reached for many environmental issues, such as energy (Davis et al. 2011), air pollution (Lin et al. 2014[1]), material use (Wiedmann et al. 2013), land use (Weinzettel et al. 2013), biomass (Peters et al. 2012), water (Hoekstra and Mekonnen 2012), and biodiversity (Lenzen et al. 2012[2]). This line of research has considerable methodological and conceptual overlap with the work on trade in value added (Johnson and Noguera, 2012, Koopman et al. 2014, Timmer et al. 2014b), but so far there has been very little attempt to formally link these two independent lines of research. That is the objective of this paper.

In the 21st century, it is difficult to reasonably assume that a country can be unconnected to GVCs. As a result, a share of a country's value added or emissions generated from the production of exported products (intermediate or final goods and services) used to fulfill foreign

---

[1] Lin et al. (PNAS, 2013) shows that 12-24% of sulfate concentrations over the western United States on a daily basis is due to the export-related Chinese pollution.

[2] Lenzen et al. (Nature, 2012) discovered that about 30% of global species threats are due to international trade.

final demand directly and indirectly has been increasing for both developed and developing economies. The converse to this is that a country's final consumption causes emissions in other countries by its relation with imports of foreign goods and services. These effects are not marginal. International trade accounts for one-quarter of global emissions, but the contributions of exports to a country's territorial emissions (median 29%, range 8–64%, year 2007) and imports to a country's consumption-based emissions (median 49%, range 6–196%, year 2007) are significant (Andrew and Peters 2013). International trade plays a relatively larger role for small and trade-dependent countries (Peters and Hertwich 2008). These effects are growing over time, and the net transfer of emissions (production minus consumption) via international trade from developing countries to developed countries increased from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008, which exceeds the Kyoto Protocol standards for emissions reductions (Peters et al. 2011). All these facts clearly imply that a country's emissions level from the perspectives of both producers and consumers is crucially subject to its position and the extent of its participation, directly or indirectly, in GVCs through international trade.

Better understanding of the relationship between emissions and GVCs requires a consistent and well-defined accounting system, which can provide proper measurements to trace value added and the amount of emissions in each stage of production and trade from different perspectives along the GVCs consistently and systemically.

In building such a unified accounting framework, existing efforts toward the measurement of embodied emissions in trade, based on multi-regional input–output (MRIO) models, provide a good starting point (e.g., Peters 2008; Peters and Hertwich 2008a; Hertwich and Peters 2009; Kanemoto et al. 2012; Meng et al. 2013). These efforts have significantly enhanced our understanding of embodied emissions in trade, and provide complete account of embodied emissions in global supply chains at country aggregates, but suffers from the difficulties to associate embodied (virtual) emission flows with gross bilateral trade flows, especially at the sector/product level (Atkinson et al., 2011), thus limits its policy relevance such as board carbon tax design (Atkinson et al., 2013) and properly separate self and shared responsibilities for carbon leakage (Peters, 2008). This forces many practitioners to use alternative methods based on bilateral trade input output models (BTIO) when accounting embodied emissions linking to a specific gross trade flow is needed thus often cause confusions among different emission estimates (generate different emission estimates for the same bilateral trade flows, will come back to this later in section 2). (**Glen may have more to add on this issue)**

By integrating recent international trade literature on gross trade accounting and environment economics literature on embodied emission trade and carbon footprint, this paper made following new contributions:

First, we generalized all the existing measures related to embodied emissions in the environmental economics literature, consistently define various trade related embodied emission measures at country, industry, bilateral and product levels and clearly quantifies their relationship in precise mathematical terms. We also defined trade in emission measure that is fully consistent with gross bilateral trade flows, overcame the disadvantages of existing measures discussed by Atkinson et al. (2011), thus integrating the so called MRIO model-based and BTIO model-based embodied emission measures in the environmental economics literature into a unified methodological framework[3].

Second, integrating with gross trade accounting method in recent international economics literature, we are able to measure trade in value-added and trade in emissions at country, bilateral, and sector/product levels in one unified accounting framework. Such a framework is not only able to measure value-added and emissions generated from each production stage (slice the value chain), but can also identify the special trade routes by which value-added and emissions are created, transferred, and consumed. By combining value-added and emissions accounting in a consistent way, the potential environmental cost along GVCs can also be estimated (e.g. emissions with per unit of value-added created) from different perspectives (production, consumption and trade). This provides a comprehensive index of emission intensity along GVCs that quantifies the amounts of emissions have been generated when one unit of GDP is created in each stage of production and trade through various GVC routes. As we will show later in this paper, these detailed quantitative information helps us gain deeper understanding of the relationship between emission intensity and a country's position and participation in GVCs.

Third, we demonstrated that the distinction between the forward and backward industrial-

[3] The existence of both BTIO and MRIO based measures in the large body of embodied emissions literature is due to two reasons: 1) when MRIO table is not available, using national IO table and international trade statistics, embodied emissions in bilateral trade can still be estimated. However, biases may occur since trade in intermediate exports is treated as exogenous variable in a BTIO model. 2) Using MRIO can remove such estimation biases but once intermediate trade is treated as endogenous variable, the difficulty will come from how to properly allocate embodied emissions in gross intermediate trade flows. This remains unsolved in the existing literature until this paper. In this sense, we unified the two analytical frameworks into MRIO model and enable it is able to provide all emission measures derived from both MRIO and BITO in the existing literature.

linkage is the key to properly measure embodied emissions at the disaggregate level the first time in the literature. We use a traditional two-country, two-sector model to provide a simple but transparent explanation of the difference between the forward and backward industrial-linkage-based decomposition techniques originally developed by Leontief (1936). We show that using the forward industrial-linkage-based decomposition, the total emissions from a country/industry can be traced according to where and by which downstream GVC routes their associated gross output are used. It is consistent with the production-based National Emission Inventory (NEI) according to the economic activities of residential institutions as defined by the System of National Accounts (SNA), similar to GDP by-industry statistics (de Haan and Keuning 1996, 2001; Pedersen and de Haan 2006). Using the backward industrial-linkage-based decomposition, we show that the total emissions from all production stages of a final good or service in a global value chain can also be fully identified. Both decomposition methods produce the same total emission estimates for a country at the aggregate level, but at the sector or bilateral sector level, they become different.

Fourth, we illustrate by both math derivation and empirical examples that measuring global emissions generated by a country's gross exports and tracing its source structure requires extending Leontief's original method to decompose gross intermediate trade flows across countries according to their final absorption. We follow the idea presented in the recent innovative work of Koopman et al. (2014), and Wang et al. (2013), in which they decompose all bilateral intermediate trade flows according to their final destination and express gross intermediate trade flows as destination countries' final demands. This key technical step successfully converts gross outputs (and thereby gross bilateral intermediate exports)—usually endogenous variables in standard MRIO models—to exogenous variables in their gross trade accounting framework. Applying this technique to measure global emissions in gross exports, we present a bridge to consistently link production-based and consumption-based accounts of emissions. We further decompose emissions generated from production of a country's GDP into international trade related and unrelated portions thus clearly distinguish emissions of self-responsibility (emissions from production satisfies domestic final demands without through international trade) and shared responsibility (emission from production satisfies domestic final demands through international trade) between producers and consumers located in different territories as well as their relative economic benefit/environment cost ratio first time in the literature.

Finally, we report a number of applications based on the World Input–Output Database

(WIOD[4]) to illustrate the potential of this new integrated accounting frameworks to deepen our understanding of the impact of global value chains on the environment. For example, by clearly distinguishing emissions generated from different GVC production routes the first time in the literature, we find that environmental cost for generating one unit of GDP only through domestic routes is lower than that created through international trade for most G-20 countries in recent decades. The main driver is the high-carbon-intensity trade in intermediates, which has grown rapidly during the period we have data (1995-2009). More importantly, previous literatures emphasis "carbon leakage" between developed and developing countries, while the ability to decompose both value-added and emission production and absorption by GVC routes of our accounting method enable us find such leakage also happens among developing countries, and is increasingly becoming the major source of "carbon leakage" in the global production and trade system. For instance, carbon emissions generated by the production of the gross bilateral trade flows between China and other non-Annex B countries (developing economies) increased dramatically from just 5% of trade related global emissions in 1995 to nearly 20% in 2009. This share for coal based carbon emissions associated with this same bilateral route has reached nearly 30% in 2009. This could be a great concern since both China and other non-Annex B countries have relatively weak environmental regulations. Without urgent action from the international community, such trend will continue and make any international emission reduction agreement become less important. As another example, we show that the production of Chinese textile and ICT exports is relative cleaner and competitive based on forward industrial linkage based emission indicators, but it is much more carbon intensive if based on backward industrial linkage based emission indicators due to its upstream sectors (such as electricity, metal, glass production) are more carbon intensive than most developed countries. This implies that China's comparative advantage in many manufacturing sectors in the world market are highly related to high-carbon inputs coming from their upstream sectors such as the electricity generation industries, which have little direct exports in the traditional trade statistics, but is embodied in other Chinese manufacturing products and in fact indirectly exports to the world market extensively.

This paper is organized as follows: Section 2 presents the integrated accounting framework and defines various embodied emission measures. Section 3 presents a number of illustrative applications for tracing CO_2 emissions in GVCs. Section 4 concludes.

[4] For detailed information, see Timmer et al. (2014a).

2. Concepts and Methodology

2.1 Embodied emissions through forward and backward industrial linkage

The methods used to estimate embodied emissions[5] are rooted in the work of Leontief (1936). Leontief demonstrated that the complex linkages among different industries across countries can be expressed as various inter-industry, cross-country transactions organized into chessboard-type matrices, known as IO tables. Each column in the table represents the required inputs from other industries (including imports and direct value added) to produce the given amount of the product represented by that column. After normalization, the technical coefficient table represents the amount and type of intermediate inputs needed in the production of one unit of gross output. Using these coefficients, the gross output in all stages of production that is needed to produce one unit of final products can be estimated via the Leontief inverse. When the output (which are endogenous in a standard IO model) associated with a particular level of final demand (which are exogenous in a standard IO model) are known, the total emissions throughout the (global) economy can be estimated by multiplying these output flows with the emission-intensity coefficient (amount of emissions per unit of gross output) in each country/industry.

To illustrate how the classic Leontief method works, let us assume a two-country (home and foreign) world, in which each country produces tradable products in N differentiated industries. Products in each sector can be consumed directly or used as intermediate inputs, and each country exports both intermediate and final products. All gross output produced by country s must be used as either an intermediate or a final product at home or abroad, that is

$$X^s = \underbrace{A^{ss}X^s + Y^{ss}}_{Domestic} + \underbrace{A^{sr}X^r + Y^{sr}}_{Exports} \; r;\; s = 1,2 \tag{1}$$

where X^s is the $N\times 1$ gross output vector of country s, Y^{sr} is the $N\times 1$ final demand vector that gives demand in country r for final goods produced in s, and A^{sr} is the $N\times N$ IO input coefficient matrix, giving intermediate use in r of goods produced in s. The superscripts in A^{sr} and Y^{sr} mean that s is the producing country and r is the destination country. In (1), $A^{ss}X^s+Y^{ss}$ is domestic use of products, while $A^{sr}X^r+Y^{sr}$ is exports to foreign countries, these in turn can be split into intermediate use $A^{ss}X^s+A^{sr}X^r$ and final consumption $Y^{ss}+Y^{sr}$. The two-country production and trade system can be written as a multi-regional IO (MRIO) model in block matrix notations

[5]A clarification is needed on what is meant by "embodied". The emissions embodied in gross output/final goods or exports/imports can be defined as the emissions that occur in the production of a product. The emissions are not actually a physical part of the product, but rather, are emitted in the production of the product.

$$\begin{bmatrix} X^s \\ X^r \end{bmatrix} = \begin{bmatrix} A^{ss} & A^{sr} \\ A^{rs} & A^{rr} \end{bmatrix} \begin{bmatrix} X^s \\ X^r \end{bmatrix} + \begin{bmatrix} Y^{ss} + Y^{sr} \\ Y^{rs} + Y^{rr} \end{bmatrix}, \tag{2}$$

which shows a clear distinction between intermediate use (*AX*) and final consumption (*Y*). The intermediate use can be either at domestic market (diagonals) or exported to/imported from (off-diagonals) foreign countries, and likewise for the final consumption. In this model, the final consumption is exogenous, while intermediate use is endogenous. After rearranging terms, we have

$$\begin{bmatrix} X^s \\ X^r \end{bmatrix} = \begin{bmatrix} I - A^{ss} & -A^{sr} \\ -A^{rs} & I - A^{rr} \end{bmatrix}^{-1} \begin{bmatrix} Y^{ss} + Y^{sr} \\ Y^{rs} + Y^{rr} \end{bmatrix} = \begin{bmatrix} B^{ss} & B^{sr} \\ B^{rs} & B^{rr} \end{bmatrix} \begin{bmatrix} Y^s \\ Y^r \end{bmatrix}, \tag{3}$$

where B^{sr} denotes an $N \times N$ block matrix, commonly known as the Leontief inverse, which is the total requirement matrix that gives the amount of gross output in producing country *s* required for a one-unit increase in final demand in country *r*. The diagonal terms B^{ss} differ from the "local" Leontief inverse $L^{ss} = (I - A^{ss})^{-1}$ due to the inclusion of off-diagonal terms via the inverse operation. Y^s is an $N \times 1$ vector that gives global use of final products from country *s*, including domestic final products sales Y^{ss} and final products exports Y^{sr}.

The intuition behind equation (3) is as follows. When \$1 of final products (either domestic sales or exports) is produced, a first round of emissions is generated (denote as P). These are the direct emissions induced by the \$1 of final products. To produce these products, intermediate inputs are required. The production of these intermediate inputs also generates emissions. This is the second round, or indirect, emissions induced by the \$1 of final products. Such a process to generate indirect emissions continues via additional rounds of production throughout the economy, as intermediate inputs are used to produce other intermediate inputs. The total amount of emissions induced by the \$1 of final products is equal to the sum of direct emissions and all rounds of indirect emissions generated from the process of producing the \$1 of final products. Expressing this process mathematically using the terms defined above, we have

$$GHG = P + PA + PAA + PAAA + ... = P(I + A + A^2 + A^3 + ...) = P(I - A)^{-1} = PB \quad (4)^6.$$

It can be shown that the power series of matrices is convergent and the inverse matrix exists as long as *A* has full rank (Miller and Jones 2009).

For our later sector level analysis, it is worthwhile to break Equations (2) and (3) into

[6] Since y =1, it is omitted.

sectoral details. For N=2, this can be re-written by element as follows:

$$\begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} = \begin{bmatrix} a_{11}^{ss} & a_{12}^{ss} & a_{11}^{sr} & a_{12}^{sr} \\ a_{21}^{ss} & a_{22}^{ss} & a_{21}^{sr} & a_{22}^{sr} \\ a_{11}^{rs} & a_{12}^{rs} & a_{11}^{rr} & a_{12}^{rr} \\ a_{21}^{rs} & a_{22}^{rs} & a_{21}^{rr} & a_{22}^{rr} \end{bmatrix} \begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} + \begin{bmatrix} y_1^{ss} + y_1^{sr} \\ y_2^{ss} + y_2^{sr} \\ y_1^{rs} + y_1^{rr} \\ y_2^{rs} + y_2^{rr} \end{bmatrix} \qquad (2a)^{7}$$

Domestic IO Coefficients

Import IO Coefficients

$$\begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} = \begin{bmatrix} 1-a_{11}^{ss} & -a_{12}^{ss} & -a_{11}^{sr} & -a_{12}^{sr} \\ -a_{21}^{ss} & 1-a_{22}^{ss} & -a_{21}^{sr} & -a_{22}^{sr} \\ -a_{11}^{rs} & -a_{12}^{rs} & 1-a_{11}^{rr} & -a_{12}^{rr} \\ -a_{21}^{rs} & -a_{22}^{rs} & -a_{21}^{rr} & 1-a_{22}^{rr} \end{bmatrix}^{-1} \begin{bmatrix} y_1^{ss} + y_1^{sr} \\ y_2^{ss} + y_2^{sr} \\ y_1^{rs} + y_1^{rr} \\ y_2^{rs} + y_2^{rr} \end{bmatrix},$$

$$= \begin{bmatrix} b_{11}^{ss} & b_{12}^{ss} & b_{11}^{sr} & b_{12}^{sr} \\ b_{21}^{ss} & b_{22}^{ss} & b_{21}^{sr} & b_{22}^{sr} \\ b_{11}^{rs} & b_{12}^{rs} & b_{11}^{rr} & b_{12}^{rr} \\ b_{21}^{rs} & b_{22}^{rs} & b_{21}^{rr} & b_{22}^{rr} \end{bmatrix} \begin{bmatrix} y_1^{ss} + y_1^{sr} \\ y_2^{ss} + y_2^{sr} \\ y_1^{rs} + y_1^{rr} \\ y_2^{rs} + y_2^{rr} \end{bmatrix} \qquad (3a)$$

where each element above is now a scalar: x_j^s is the gross output of sector *j* in country *s*; y_i^{sr} represents final goods produced by sector *i* in country *s* for consumption in country *r* (*i,j* = 1,2); a_{ij}^{sr} is the direct IO coefficient that measures the intermediate inputs produced in sector i of country *s* that are used in the production of one unit of gross output in sector j of country *r*, and b_{ij}^{sr} is the total requirement coefficient that gives the total amount of the gross output of sector i in country *s* needed to produce an extra unit of the sector j's final product in country r. Other coefficients have similar economic interpretations.

The final demand vector in (3a) can be condensed as $\begin{bmatrix} y_1^{ss}+y_1^{sr} & y_2^{ss}+y_2^{sr} & y_1^{rs}+y_1^{rr} & y_2^{rs}+y_2^{rr} \end{bmatrix}^T = \begin{bmatrix} y_1^s & y_2^s & y_1^r & y_2^r \end{bmatrix}^T$. Define the direct emission intensity as $f_j^c \equiv p_j^c / x_j^c$ for *c* = *s*,*r*, *j*=1,2, then the estimation and decomposition of the country- and sector-level production of emissions can be expressed as

$$\hat{F}B\hat{Y} = \begin{bmatrix} f_1^s & 0 & 0 & 0 \\ 0 & f_2^s & 0 & 0 \\ 0 & 0 & f_1^r & 0 \\ 0 & 0 & 0 & f_2^r \end{bmatrix} \begin{bmatrix} b_{11}^{ss} & b_{12}^{ss} & b_{11}^{sr} & b_{12}^{sr} \\ b_{21}^{ss} & b_{22}^{ss} & b_{21}^{sr} & b_{22}^{sr} \\ b_{11}^{rs} & b_{12}^{rs} & b_{11}^{rr} & b_{12}^{rr} \\ b_{21}^{rs} & b_{22}^{rs} & b_{21}^{rr} & b_{22}^{rr} \end{bmatrix} \begin{bmatrix} y_1^s & 0 & 0 & 0 \\ 0 & y_2^s & 0 & 0 \\ 0 & 0 & y_1^r & 0 \\ 0 & 0 & 0 & y_2^r \end{bmatrix}$$

[7] The elements in the diagonal block of the A matrix are domestic input-output coefficients, while elements in the off-diagonal block are import input –output coefficients. The Y matrix is similar.

$$
=\begin{bmatrix} f_1^s b_{11}^{ss} y_1^s & f_1^s b_{12}^{ss} y_2^s & f_1^s b_{11}^{sr} y_1^r & f_1^s b_{12}^{sr} y_2^r \\ f_2^s b_{21}^{ss} y_1^s & f_2^s b_{22}^{ss} y_2^s & f_2^s b_{21}^{sr} y_1^r & f_2^s b_{22}^{sr} y_2^r \\ f_1^r b_{11}^{rs} y_1^s & f_1^r b_{12}^{rs} y_2^s & f_1^r b_{11}^{rr} y_1^r & f_1^r b_{12}^{rr} y_2^r \\ f_2^r b_{21}^{rs} y_1^s & f_2^r b_{22}^{rs} y_2^s & f_2^r b_{21}^{rr} y_1^r & f_2^r b_{22}^{rr} y_2^r \end{bmatrix} \tag{5}
$$

This matrix gives estimates of the sector and country sources of emissions in each country's final goods production. Each element in the matrix represents emissions from a source industry of a source country directly or indirectly generated in the production of final products (consumed in both the domestic and foreign markets) in the source country. Looking at the matrix along the rows yields the distribution of emissions created from one country/sector across all countries/sectors. For example, the first element of the first row, $f_1^s b_{11}^{ss}(y_1^{ss} + y_1^{sr})$, is the emissions created by sector 1 in country s to produce its final goods for both domestic sales and exports. The second element, $f_1^s b_{12}^{ss}(y_2^{ss} + y_2^{sr})$, is the emissions generated by sector 1 in country s to produce intermediate input used by sector 2 in country s to produce its final products. The third and fourth elements, $f_1^s b_{11}^{sr}(y_1^{rs} + y_1^{rr})$ and $f_1^s b_{12}^{sr}(y_2^{rs} + y_2^{rr})$, are, respectively, emissions from sector 1 in country s generated in the production of intermediate inputs used by the 1st and 2nd sectors in country r to produce country r's final products. Therefore, summing up the first row of the matrix, we obtain the total emissions generated from sector 1 in country s. This can be expressed mathematically as

$$
\begin{aligned} p_1^s &= f_1^s x_1^s = f_1^s (b_{11}^{ss} y_1^s + b_{12}^{ss} y_2^s + b_{11}^{sr} y_1^r + b_{12}^{sr} y_2^r) \\ &= \left[f_1^s b_{11}^{ss} y_1^{ss} + f_1^s b_{12}^{ss} y_2^{ss} + f_1^s b_{11}^{sr} y_1^{rs} + f_1^s b_{12}^{sr} y_2^{rs} \right] + \left[f_1^s b_{11}^{ss} y_1^{sr} + f_1^s b_{12}^{ss} y_2^{sr} + f_1^s b_{11}^{sr} y_1^{rr} + f_1^s b_{12}^{sr} y_2^{rr} \right] \end{aligned} \tag{6}
$$

which distributes the total emissions produced in a country/industry according to where its total gross output are finally absorbed. The value of p_j^s is consistent with the production-based National Emission Inventory (NEI) and is similar to GDP-by-industry statistics[8].

Looking at the $\hat{F} B \hat{Y}$ matrix down a column yields emissions estimates from all countries/sectors across the world for the production of final products in a particular country/sector. For example, the second element in the first column, $f_2^s b_{21}^{sr}(y_1^{ss} + y_1^{sr})$, is the amount of emissions generated in sector 2 of country s to produce intermediate inputs used by sector 1 in country s to

[8]For the difference between the production-based NEI estimates from the MRIO table and the UNFCCC NEI, see Peters (2008).

produce final products, and the third and fourth elements, $f_1^r b_{11}^{rs}(y_1^{ss}+y_1^{sr})$ and $f_2^r b_{21}^{rs}(y_1^{ss}+y_1^{sr})$, respectively, are emissions generated in sectors 1 and 2 of (foreign) country *r* to produce intermediate inputs used by sector 1 in country *s* in the production of final products.

Adding up all elements in the first column gives the global emissions generated by the production of final products in sector 1 of country *s*, denoted as $p(y_1^s)$, i.e

$$p(y_1^s)=(f_1^s b_{11}^{ss}+f_2^s b_{21}^{ss}+f_1^r b_{11}^{rs}+f_2^r b_{21}^{rs})y_1^s, \tag{7}$$

It traces total emissions generated by the production of a final product in a particular country/industry according to where the needed intermediate inputs are produced along each stage (represented by different industries located in different countries) of the global production chain. This is the global "carbon footprint" of the consumption of sector 1's products from country *s*. The last two terms represent imported emissions.

In summary, the sum of the $\hat{F}B\hat{Y}$ matrix along a row represents the production-based emissions and shows how each country's emissions in a particular sector are distributed to final consumption (across columns) of all downstream countries/sectors (including itself), thus decomposes each country's total emissions by industry according to where the final consumption is made. It traces forward industrial linkages (downstream) from an emitter's perspective. The sum of the $\hat{F}B\hat{Y}$ matrix along a column accounts for all upstream countries/sectors' emissions to the production of a specific country/sector's final products (carbon footprint); it traces backward industrial linkages across upstream countries/industries (as different stages of production) from a user perspective, thus decomposes the total global emissions from the production of a country/sector's final goods and services according to where each of the needed intermediate inputs is produced.

As an example, in the chemical sector, the producer's perspective includes the emissions created by the production of chemicals that are embodied in the final goods exports of chemical products themselves (direct domestic emissions exports), as well as in the final exports of metal products, computers, consumer appliances, and machineries that use chemicals as inputs (indirect domestic emissions exports). Such a forward linkage perspective is consistent with the literature on the emissions content of trade. On the other hand, decomposition from a user perspective includes all upstream sectors/countries' contributions to emissions in a specific sector/country's final goods exports. For instance, in the automobile industry, it includes emissions generated in the automobile production itself as well as emissions embodied in inputs from all other upstream sectors/countries (such as rubber from country A, glass from country B, steel from country C, design and testing from the home country) used to produce an automobile for exports by the home country. Such a backward industrial-linkage-based perspective aligns well with case studies of emissions by a specific final product in the literature.

Each of these two different ways to decompose global total emissions has its own interpretations and thus different roles in environmental policy analysis. The decomposition of emissions by producing industry can address questions such as "who generates the emissions for whose consumption?" thus providing a starting point for the discussion of shared responsibility between producer and consumer at the industry level; while the decomposition of total emissions generated to produce a final product is able to answer questions such as "what is the global emissions level and what is the emission source (country/industry) structure required to produce a car in Germany compared to that for China?" and can attribute the total emissions for a final product to each stage of production in the global supply chain, thus providing facts that improve understanding of the common but differentiated responsibilities among different production stages along each global supply chain.

With a clear understanding of how total national emissions by industry and total global emissions by the production of final goods and services at the country-sector level can be correctly estimated and decomposed by the standard Leontief method (equation (5) or the $\hat{F}B\hat{Y}$ matrix), we formally specify the decomposition methods used in this paper and their relations to other IO model based methods proposed in the literature.

2.2 Downstream decomposition: Decompose emissions from a country/industry based on forward industrial linkage

Extending equation (2) to a G country setting, the gross output production and use balance, or the row balance condition of a MRIO table becomes

$$X^s = A^{ss}X^s + \sum_{s\neq r}^{G} A^{sr}X^r + Y^{ss} + \sum_{s\neq r}^{G} Y^{sr} = A^{ss}X^s + Y^{ss} + \sum_{s\neq r}^{G} E^{sr} = A^{ss}X^s + Y^{ss} + E^{s*} \tag{8}$$

where $E^{s*} = \sum_{s\neq r}^{G} E^{sr}$ is the total gross export of country s. Rearranging (8) gives

$$X^s = (I - A^{ss})^{-1} Y^{ss} + (I - A^{ss})^{-1} E^{s*} \quad (9)$$

With a further decomposition of the gross exports into exports of intermediate/final products and their final destination of absorption, it can be shown that

$$\begin{aligned} (I - A^{ss})^{-1} E^{s*} &= (I - A^{ss})^{-1} \left(\sum_{r \neq s}^{G} Y^{sr} + \sum_{r \neq s}^{G} A^{sr} X^r \right) \\ &= \sum_{r \neq s}^{G} B^{sr} Y^{rs} + \sum_{r \neq s}^{G} B^{sr} A^{rs} (I - A^{ss})^{-1} Y^{ss} + \sum_{r \neq s}^{G} B^{ss} Y^{sr} + \sum_{r \neq s}^{G} B^{sr} Y^{rr} + \sum_{r \neq s}^{G} B^{sr} \sum_{t \neq s,r}^{G} Y^{rt} \end{aligned} \quad (10)^{9}$$

Inserting (10) into (9) and pre-multiplying the direct emission intensity diagonal matrix $\hat{F}$, we obtain an equation that decomposes total emissions by industry into different components.

$$P^s = \hat{F}^s X^s = \underbrace{\hat{F}^s L^{ss} Y^{ss}}_{(1)} + \underbrace{\hat{F}^s L^{ss} \sum_{r \neq s}^{G} A^{sr} \sum_{t}^{G} B^{rt} Y^{ts}}_{(2)} + \underbrace{\hat{F}^s \sum_{r \neq s}^{G} B^{ss} Y^{sr}}_{(3)} + \underbrace{\hat{F}^s \sum_{r \neq s}^{G} B^{sr} Y^{rr}}_{(4)} + \underbrace{\hat{F}^s \sum_{r \neq s}^{G} B^{sr} \sum_{t \neq s,r}^{G} Y^{rt}}_{(5)} \quad (11)^{10}$$

Here, $L^{ss} = (I - A^{ss})^{-1}$ is the local Leontief inverse.

There are five terms in equation (11), each of which represents emissions generated by the industry in its production to satisfy different segments of the global market. All the emissions that occur in region *s* are a result of various elements of production.

- The first term: domestically produced and consumed final goods and services ($L^{ss}Y^{ss}$).
- The second term: domestically produced intermediate goods exports ($L^{ss} A^{sr} \sum_{t}^{G} B^{rt} Y^{ts}$) which are used by other countries to produce either intermediate or final goods and services shipped back to the source country as imports and consumed there. [11]
- The third term: domestically produced final goods and service exports that are consumed by all of its trading partners ($B^{ss}Y^{sr}$).
- The fourth term: domestically produced intermediate goods and services exported to country *r* for the production of final products consumed in country *r* ($B^{sr}Y^{rr}$)
- The fifth term: domestically produced intermediate goods exports to other countries producing their final goods and service exports to third countries $B^{sr}Y^{rt}$).

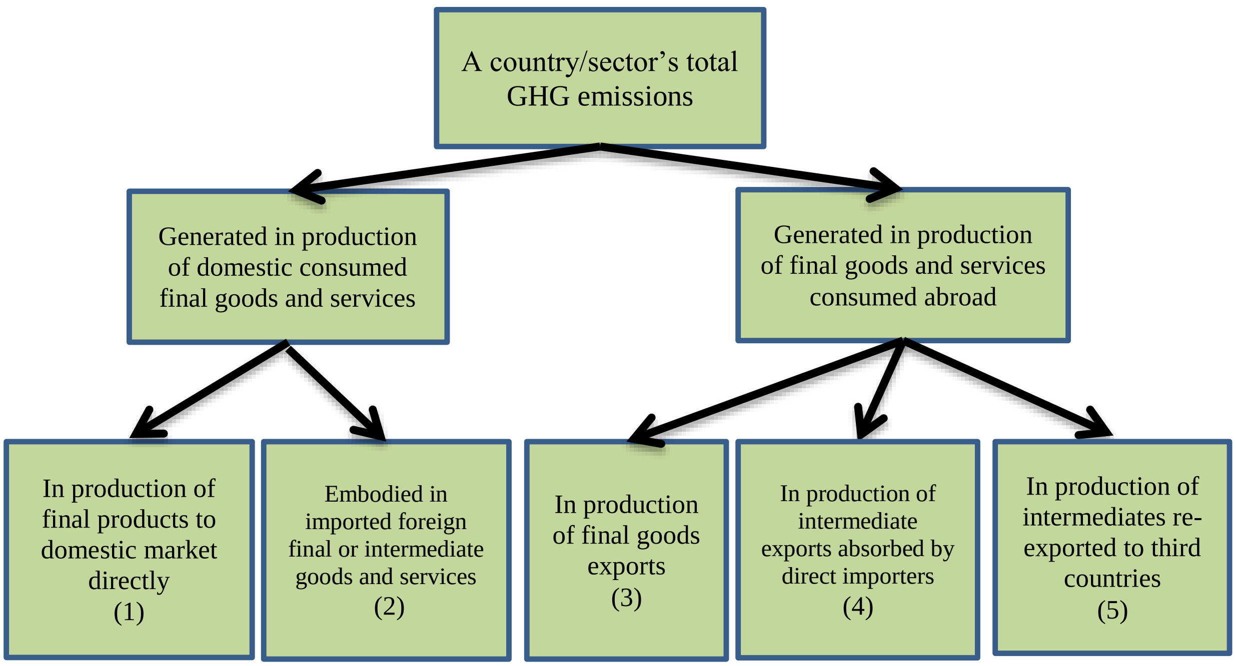
[9] A detailed mathematical proof of equation (10) is provided in Appendix A.1.

[10] The second term (2) on the right side in equation (11) equals to the sum of the first two terms on the right side in equation (10) (for detailed proof, see the appendix in Wang et al. 2013)

[11] This indicates the second term in (11) can be further split according to a country's final goods and intermediate goods imports and each particular trading partner that the imports come from.

Note the summation in the last three terms indicates that these emissions generated by export production can be further split into each trading partner's market. The sum of the last three terms gives the amount of emissions exports, and the sum of the last four terms in each bilateral route is the "Emissions Embodied in Bilateral Trade" (EEBT). Both of these amounts are frequently used in the literature on embodied emissions in trade, which we will discuss in detail later in this paper. The disaggregated accounting for total emissions by industry based on forward industrial linkage (downstream decomposition) made by equation (11) is also diagrammed in Figure 1. The number in the lowest level box corresponds to the terms in equation (11).

Figure 1 GHG emissions production, by sources of final demand – Forward industrial-linkage-based decomposition



2.3 Upstream decomposition: Decompose emissions from final goods and services by production stages in a global supply chain based on backward industrial linkage

In the following we estimate the total emissions generated by a final product along the global supply chain identified by the last stage of production: a particular industry i located in a specific country s, which is denoted by y_i^s to be consistent in notation with the previous section. To produce

y_i^s, activities x_j^s in industry j = 1,…, N in each country s = 1,…,G are needed[12]. We first need to know the levels of all gross outputs x_j^s associated with the production of y_i^s. This is estimated using the Leontief inverse as in equations (3) and (5).

To be more specific to our current analysis, let us extend equations (3) and (5) to cover any number of countries (G) and sectors (N). Then we obtain the following equations.

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^G \end{bmatrix} = \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} Y^1 \\ Y^2 \\ \vdots \\ Y^G \end{bmatrix} \tag{12}$$

$$\hat{F}_c B\hat{Y} = \begin{bmatrix} \hat{F}_c^1 & 0 & \cdots & 0 \\ 0 & \hat{F}_c^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{F}_c^G \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} \hat{Y}^1 & 0 & \cdots & 0 \\ 0 & \hat{Y}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{Y}^G \end{bmatrix}$$

$$= \begin{bmatrix} \hat{F}_c^1 B^{11} \hat{Y}^1 & \hat{F}_c^1 B^{12} \hat{Y}^2 & \cdots & \hat{F}_c^1 B^{1G} \hat{Y}^G \\ \hat{F}_c^2 B^{21} \hat{Y}^1 & \hat{F}_c^2 B^{22} \hat{Y}^2 & \cdots & \hat{F}_c^2 B^{2G} \hat{Y}^G \\ \vdots & \vdots & \ddots & \vdots \\ \hat{F}_c^G B^{G1} \hat{Y}^1 & \hat{F}_c^G B^{G2} \hat{Y}^2 & \cdots & \hat{F}_c^G B^{GG} \hat{Y}^G \end{bmatrix} \tag{13}$$

With G countries and N sectors, A, B, $\hat{F}$ and $\hat{Y}$ are all $GN \times GN$ matrices. B^{sr} denotes the $N \times N$ block Leontief (global) inverse matrix, F_c^s is a 1 by N vector of direct emission intensities in country s, placed along the diagonal of the GN by GN matrix of $\hat{F}$. The subscript c represents type of energies and non-energies. Five types are considered: (1) coal, (2) petroleum, (3) gas, (4) waste, and (5) others (non-energy). X^s is an $N \times 1$ vector that gives the total gross output of country s; $Y^s = \sum_r^G Y^{sr}$ is also an $N \times 1$ vector that gives the global use of final goods produced by s. Each

[12] Production stages in the global supply chain are identified by each x_j^s, the maximum number of production stages of a specific supply chain in this accounting framework is G *by* N, assuming industries with the same classification but located in different countries produce differentiated products and so are located in different production stages of the global supply chain. Such an assumption is similar to the Armington assumption that has been widely used in CGE models for decades.

column of the $B\hat{Y}$ matrix of Equation (13) is a *GN* by 1 vector, the number of non-zero elements in such a column vector represents the number of production stages in our accounting framework for the global supply chain of a particular final good or service y_j^s.

Based on equation (13), we can decompose the total emissions of a final good or service by production stages and types of energy in a global supply chain based on backward industrial linkage as follows.

$$P_c(Y^s) = \hat{F}_c^s B^{ss} Y^s + \sum_{r \neq s}^{G} \hat{F}_c^r B^{rs} Y^s \textit{ for } c = 1,2,3,4,5 \tag{14}$$

$$P(Y^s) = \sum_{c=1}^{5} P_c(Y^s) \tag{15}$$

The first term in equation (14) consists of the diagonal elements in the last matrix of equation (13), representing emissions generated in domestic production process; while the second term in equation (14) is the sum of off-diagonal elements across the row and in a column in the last matrix of equation (13), measuring emissions generated in foreign production processes. The summation in the second term indicates that these emissions generated by foreign production can be further split according to their source countries. Note that $\sum_{c=1}^{5} F_c^s = F^s$, that is, emission intensities by energy types in each country/industry sum to the total emission intensity of that country/industry. Therefore, equation (15) measures the total global emissions for the production of final products in country *s*. The decomposition of total emissions by the production of a final products in a global supply chain based on backward industrial linkage made by equations (14) is shown in Figure 2.

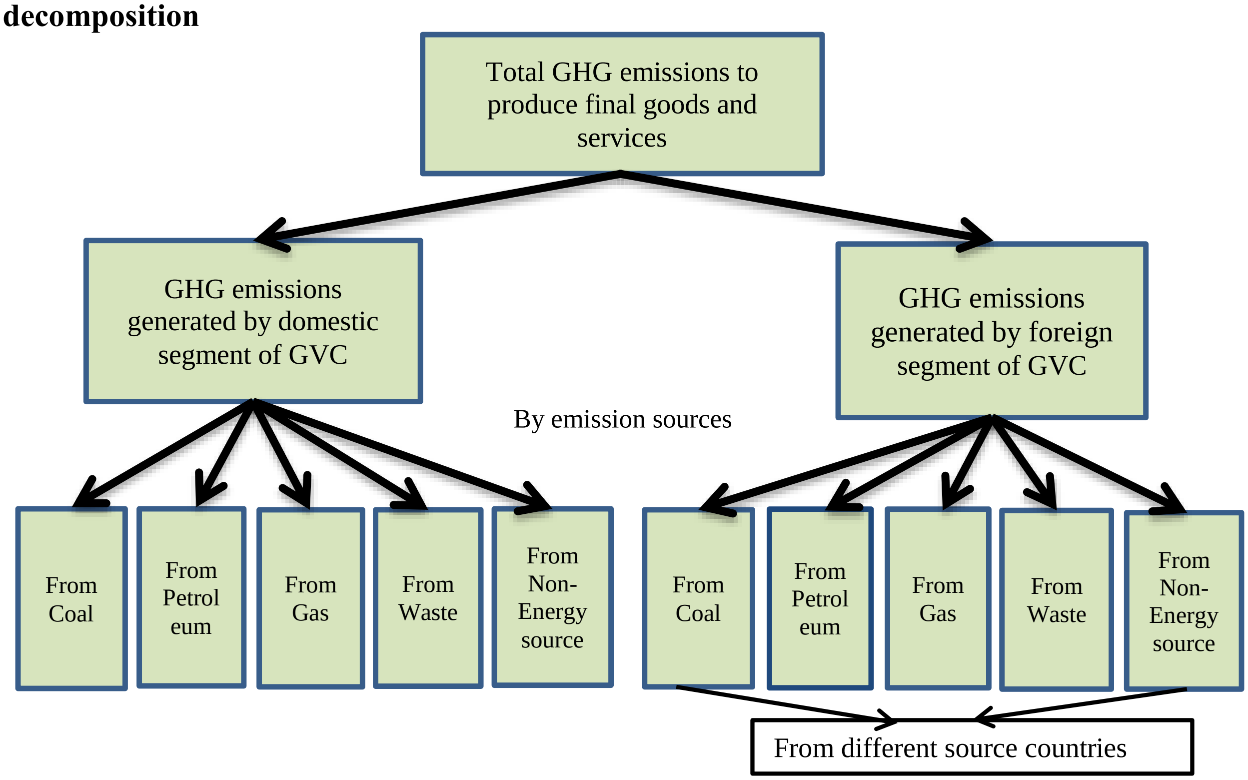
Based on equation (14), the consumption-based national emissions inventories for a particular product y_i^r can be estimated for each country as a sum weighted by consumption source structure:

$$P_c^{consumer}(y_i^{*r}) = \sum_{s}^{G} \frac{y_i^{sr}}{y_i^{*r}} P_c(y_i^{s*}) \textit{ for } c = 1,2,3,4,5 \qquad ; i = 1,2,\ldots N \tag{16}$$

Here, $y_i^{s*} = \sum_{r}^{G} y_i^{sr}$ is the total final production in country *s* of product *i* for all countries, and $y_i^{*r} = \sum_{s}^{G} y_i^{sr}$ is the total final consumption in country *r* of product *i* sourced from all countries.

Using the estimates from equation (14) and weighting by each country's source structure of the particular products it consumes, equation (16) allows one to estimate consumption-based emissions at country/product level and its results are different from emissions estimates obtained by using production emissions minus exported emissions plus imported emissions. Taking automobile as an example, the production plus net transfer method widely used in the literature only can provide estimates on how much of the emissions produced in the global auto industry is consumed in a country, which does not equal global emissions induced by the total automobile consumption in that country. However, summing over all products or industries, the total consumption-based emissions for a country will be the same regardless backward or forward linkage based computation is used.

Figure 2 GHG emissions in global supply chains – backward industrial-linkage-based decomposition



2.4 Measures of embodied emissions in trade and their role in linking production-based and consumption-based emissions accounts

In recent years, the international trade of embodied emissions has been a subject of substantial interest in both academic and policy circles. However, most MRIO-based measures of trade in embodied emissions in the literature have not made a clear distinction between emissions calculated by forward versus backward industrial linkages and often focus on the global and country aggregate level. As we will show in this section, such a distinction is not important at an aggregated level, but is crucial at a disaggregated level.

It is important to distinguish three measures of trade in embodied emissions and two measures of emissions embodied in a country's gross exports at disaggregated levels

1. Embodied emissions exports, or emissions generated in production to satisfy foreign final demand, by forward industrial linkages (EEX_F);
2. Emissions embodied in a country's gross exports through forward industrial linkages (EEG_F);
3. Embodied emissions exports, or emissions generated in production to satisfy foreign final demand, through backward industrial linkages (EEX_B);
4. Embodied emissions associated with bilateral gross trade flows that satisfy foreign final demand (EEX);
5. Emissions embodied in a country's gross exports through backward industrial linkages (EEG_B).

At a bilateral sector or country sector level, emissions exports based on forward industrial linkages (EEX_F) for sector *i* and region *s*, are the emissions generated in sector *i* to produce, directly and indirectly, gross exports from *s* to any other destination country except country *s* itself (e.g., emission exports from the US chemical sector would include emissions embodied in US steel and machinery sectors in addition to emission embodied in the US chemical sector). There are two key issues to highlight here. First, using the example of emissions exports from the US chemical industry, is that some of the emissions produced by that sector can be exported indirectly via other US sectors such as steel, because US produced chemicals are used as intermediate inputs in the production of steel exports. Second, the portion of the emissions that is associated with products first exported but eventually re-imported to satisfy domestic final demand is not part of the embodied emissions exports.

Emissions embodied in a country's gross exports, which we labeled as EEG, refer to emissions generated from the production of the country's gross exports. Because this measure focuses only on where the emissions come from but not where they are absorbed, it does not exclude the part of the emissions that is generated by producing intermediate inputs for other countries but eventually returns home via imports (i.e., is re-imported) to satisfy domestic final demand. It is conceptually similar to emissions embodied in bilateral trade (EEBT) defined by Peters (2008) and Peters et al. (2011). The EEG based on forward industry linkage, EEG_F, refers to the part of emissions generated from the production of the country's gross exports from all sectors that reflect the domestic emissions originating from a particular sector, including the portion that eventually returns (which will be labeled REE_F) via imports. Because we already have a complete decomposition of emissions by industry in equation (11), it is convenient to mathematically specify EEX_F, emissions generated in production to satisfy foreign final demand, and REE_F, emissions generated in the production of intermediate exports for other countries which are then used to produce their exports and shipped back to country *s* as follows.

$$EEX\_F^{sr} = \hat{F}^s B^{ss} Y^{sr} + \hat{F}^s B^{sr} Y^{rr} + \hat{F}^s \sum_{t \neq s,r}^{G} B^{st} Y^{tr} \tag{17}$$

$$REE\_F^{sr} = \hat{F}^s L^{ss} A^{sr} \sum_{t}^{G} B^{rt} Y^{ts} = \hat{F}^s L^{ss} A^{sr} B^{rr} Y^{rs} + \hat{F}^s L^{ss} A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{ts} + \hat{F}^s L^{ss} A^{sr} B^{rs} Y^{ss} \tag{18}$$

Equation (17) is the sum of the third and fourth terms in equation (11) plus an additional term taken from the last term of equation (11) which only sums over third country *t* re-exports to a particular trading partner *r* (without the second summation over all *r*). Equation (18) is a further decomposition of the second term in equation (11). It measures domestic emissions embodied in intermediate exports from country *s* to country *r* that return to *s* and are ultimately absorbed in *s* via all possible routes through forward industrial linkage. Both portions are emissions related to international trade but for different market segments.

We specify domestic emissions embodied in gross exports from country *s* to country *r* based on forward industrial linkages as

$$\begin{aligned} EEG\_F^{sr} = \hat{F}^s L^{ss} E^{sr} &= \underbrace{\hat{F}^s L^{ss} Y^{sr}}_{(1)} + \underbrace{\hat{F}^s L^{ss} A^{sr} \sum_{t}^{G} B^{rt} Y^{tr}}_{(2a)} \\ &+ \underbrace{\hat{F}^s L^{ss} A^{sr} \sum_{t}^{G} B^{rt} Y^{ts}}_{(2b)} + \underbrace{\hat{F}^s L^{ss} \left[A^{sr} \sum_{r \neq s}^{G} B^{rt} Y^{tt} + A^{sr} \sum_{t \neq s,r}^{G} B^{rs} Y^{st} \right]}_{(2c)} \end{aligned} \tag{19}$$

It measures what amount of domestic emissions can be generated from the production of gross exports E^{sr} in country *s*, regardless whether these gross exports are finally absorbed in importing country *r* or not. It can be decomposed into two parts:

1. Domestic emissions generated from the production of final goods exports,
2. Domestic emissions generated from the production of intermediate goods exports that are:
   2a. finally absorbed in the direct importing country *r*,
   2b. returned (re-imported) to the exporting country *s*, or
   2c. re-exported to a third country *t*.

It is identical to the "Emissions Embodied in Bilateral Trade" (EEBT) defined by others (Peters 2008; Peters and Hertwich 2008) in the literature on embodied emissions in trade. It is easy to see that REE_F^{sr} defined by equation (18) is exactly the third term in equation (19). We can show that, at the bilateral-sector level, $\hat{F}^s L^{ss} E^{sr} \neq (EEX\_F^{sr} + REE\_F^{sr})$ due to indirect emissions exports through third countries. However, after aggregating over all trading partners, at the country-sector level,

$$\sum_{r \neq s}^{G} EEG\_F^{sr} = \sum_{r \neq s}^{G} (REE\_F^{sr} + EEX\_F^{sr}) = \sum_{r \neq s}^{G} \hat{F}^s L^{ss} E^{sr} \tag{20}$$

The step by step derivation of equations (18) to (20) can be found in appendix A.2. The intuition behind the derivation is simple: both EEX_F^{sr} and REE_F^{sr} require that the emissions associated with a product is consumed in destination country *r* by definition, while EEG_F^{sr} or EEBT do not have such restrictions and are concerned only where these emissions are generated, regardless of where their associated products are finally absorbed.

Similar to Peters et al. (2011), we define the balance of embodied emissions in trade, or "net emissions transfer" as

$$T^s = \sum_{r \neq s}^{G} EEX\_F^{sr} - \sum_{s \neq r}^{G} EEX\_F^{rs} \tag{21}$$

It is easy to show that T^s equals the difference between production-based and consumption-based emission inventory. That is,

$$T^r = P^{producerer}(y_i^r) - P^{consumer}(y_i^r)\,. \tag{22}$$

Embodied emissions exports calculated by backward industrial linkages at a bilateral sector or country-sector level, which we labeled as EEX_B, refer to the amount of emissions generated by the production of a particular sector's gross exports (e.g., US auto), which will include emissions produced by any domestic sectors (e.g., including US rubber, chemicals, steel, and glass) via backward industrial linkages, and is ultimately absorbed abroad or in a particular destination country. There are also two key features to take into account. First, the measure quantifies emissions to the sector whose products are exported. Second, the concept excludes the part of domestic emissions that is eventually re-imported. In general, at the country sector and bilateral sector level, EEX_F and EEX_B are not the same except by coincidence. However, once we aggregate across all sectors, the distinction between EEX_F and EEX_B disappears.

To trace emissions generated by gross trade flows at bilateral and sector levels, it is useful to think of the total domestic emissions associated with gross trade flows that is absorbed abroad, denoted by EEX, as a distinct concept from EEX_B or EEX_F in order to measure emissions embodied in a particular bilateral gross trade flows. It is also based on backward industrial linkages and is also ultimately absorbed abroad, similar to EEX_B, but does not require domestically produced emissions to be absorbed in a particular destination country. In other words, at the country sector level, this third trade-in-emissions measure is the same as EEX_B, but at the bilateral or bilateral sector level, they are different. As we will show later in this paper, EEX is the only emissions trade measure that is consistently associated with bilateral gross trade flows, while both EEX_F and EEX_B are not, due to indirect emissions trading through third countries. All these three measures exclude the part of domestic emission that first exported but eventually returns home. However, all of them are necessary to trace emission trade in gross exports beyond the country aggregate level.

Measuring emission trade based on the backwards and forwards industrial linkages at a disaggregated level is useful for different purposes. If one wishes to understand the global emissions level generated by a country's gross exports and its source structure, the backward-linkage-based emissions measures are the right one to use. If one wishes to understand the responsibility for emissions from a given sector in the country's gross exports from all sectors, one should use the forward-linkage-based measures. Earlier work has shown that these two approaches can be linked via structural path analysis (Peters and Hertwich 2006).

As we have already shown, to decompose a country/industry's total GHG emissions by source of final demand and measure domestically produced emissions embodied in a country's gross exports from all sectors based on forward industrial linkage, applying Leontief's original method is sufficient. However, for measuring global emissions generated by a country's gross exports and tracing its source structure based on backward industrial linkage, Leontief's original method will not be sufficient, as it does not provide a way to decompose gross intermediate trade flows across countries according to their final absorption, as illustrated in a recent NBER working paper by Wang et al. (2013).

Following Wang et al. (2013)'s innovative intermediate trade flow decomposition method, we define our bilateral emissions trade measures based on backward industrial linkage by

$$\begin{aligned} EEX^{sr} &= (F^s B^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) \\ &+ (F^s L^{ss})^T \# \left\{ (A^{sr} B^{rr} \sum_{t \neq s,r}^{G} Y^{rt}) + (A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{tt}) + (A^{sr} \sum_{t \neq s,r}^{G} \sum_{u \neq s,t}^{G} B^{rt} Y^{tu}) \right\} \end{aligned} \tag{23}$$

$$\begin{aligned} EEX\_B^{sr} &= (F^s B^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) \\ &+ (F^s L^{ss})^T \# \left\{ (\sum_{t \neq s,r}^{G} A^{st} B^{tt} Y^{tr}) + (A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{tr}) + (\sum_{t \neq s,r}^{G} \sum_{u \neq s,t}^{G} A^{st} B^{tu} Y^{ur}) \right\} \end{aligned} \tag{24}$$

where "#" is an element-wise matrix multiplication operator[13]. To facilitate the understanding of the three terms in the emissions trade measure defined in equation (23), we provide the following intuitive interpretations.

The the 1st term, $(F^s B^{ss})^T \# Y^{sr}$, represents domestic emissions generated by the production of final exports from country *s* to country *r*. The 2nd term, $(F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr})$, represents domestic emissions generated by the production of intermediate exports from country *s* used by direct importer (country *r*) to produce final goods and services which are consumed in country *r*. The 3rd term, $(F^s L^{ss})^T \# \{\ldots\}$ represents domestic emissions generated by the production of intermediate exports from country *s* used by the direct importer (country *r*) to produce intermediate or final goods and services that are re-exported to a third country *t*. The three elements in the

[13]For example, when a matrix is multiplied by $n \times 1$ column vector, each row of the matrix is multiplied by the corresponding row element of the vector.

parenthesis, $A^{sr}B^{rr}\sum_{t\neq s,r}^{G}Y^{rt}$, $A^{sr}\sum_{t\neq s,r}^{G}B^{rt}Y^{tt}$, and $A^{sr}\sum_{t\neq s,r}^{G}\sum_{u\neq s,t}^{G}B^{rt}Y^{tu}$ show how the re-exports are produced in country *r* by using intermediate exports from country *s* as inputs. They represent final goods re-exports, intermediate goods re-exports for third countries' domestically consumed final goods, and intermediate goods re-exports for third countries' final goods exports, respectively.

It is interesting to note that the difference between EEX^{sr} (23) and EEX_B^{sr} (24) appears in only the third country term (the third term). The former includes emissions absorbed not only by country *r*, but also by third countries *t* and *u* (last three terms in equation 24). The latter includes not only emissions exports from country *s* embodied in its own gross exports to country *r* (the 1st and 2nd terms in equation 24, which are the same as the first two terms in equation 23), but also emissions exports by country *s* embodied in its gross exports to third country *t*, that are finally absorbed by country *r* (the last terms in equation 24). This illustrates why we claim that EEX^{sr} is the only measure of emission trade which is consistently associated with bilateral gross trade flows. Both emissions export measures are deviate from gross bilateral trade flows due to indirect trade through third countries.

Similar to the definition of EEG_F, we could also define EEG_B, the measure of domestic emissions generated from the production of bilateral gross exports at sector level based on backward industrial linkage, which refers to emissions from all domestic sectors induced by the production of a particular sector's gross exports to a particular trading partner or the rest of the world, including the portion of emissions associated with exported products that are eventually re-imported, REE_B.

$$\begin{aligned} EEG\_B^{sr} &= (F^sL^{ss})^T \# E^{sr} = (F^sL^{ss})^T \# Y^{sr} + (F^sL^{ss})^T \# A^{sr}\sum_{t}^{G}B^{rt}Y^{tr} \\ &+ (F^sL^{ss})^T \# A^{sr}\sum_{t}^{G}B^{rt}Y^{ts} + (F^sL^{ss})^T \# \left[A^{sr}\sum_{r\neq s}^{G}B^{rt}Y^{tt} + A^{sr}\sum_{t\neq s,r}^{G}B^{rs}Y^{st} \right] \end{aligned} \tag{25}$$

EEG_B^{sr} measures what amount of domestic emissions can be generated from all sectors in country *s* in the production of gross exports E^{sr} in country *s*, regardless of whether these exports are finally absorbed in importing country *r* or not. The four terms in equation (25) have similar interpretations to those of the four terms in equation (20); the differences are that these terms include not only domestic emissions generated by the exporting sectors, but also those of other upstream domestic sectors that contribute to the production of a particular sector's gross exports.

We define emissions embodied in intermediate exports that are first exported but ultimately returned and absorbed at home based on backward industrial linkages from country *s* to country *r* as:

$$
\begin{aligned}
REE\_B^{sr} &= (F^s L^{ss})^T \# A^{sr} \sum_{t}^{G} B^{rt} Y^{ts} \\
&= (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rs}) + (F^s L^{ss})^T \# (A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{ts}) + (F^s L^{ss})^T \# (A^{sr} B^{rs} Y^{ss})
\end{aligned}
\tag{26}
$$

It can be seen that REE_B^{sr} is exactly the third term in equation (25). We can show that EEG_B^{sr} equals the sum of equations (23) and (26) at the country aggregate level only.

$$
\sum_{r \neq s}^{G} uEEG\_B^{sr} = \sum_{r \neq s}^{G} u(EEX^{sr} + REE\_B^{sr}) = \sum_{r \neq s}^{G} F^s L^{ss} E^{sr} \tag{27}
$$

where, u is a 1 by N unit vector. Detailed proofs of equations (25) to (27) are given in appendix A.3.

To completely measure total emissions from the production of a country's gross exports, emissions generated in other countries that provide intermediate inputs for the exporting country also have to be estimated. The foreign-produced emissions embodied in a country's gross exports (FEE) can be defined as

$$
\begin{aligned}
FEE^{sr} &= (F^r B^{rs})^T \# Y^{sr} + (F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr}) \\
&+ (\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# Y^{sr} + (\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# (A^{sr} L^{rr} Y^{rr})
\end{aligned}
\tag{28}
$$

Each term in equation (28) has an intuitive interpretation. The first term, $(F^r B^{rs})^T \# Y^{sr}$, is the importer's (country *r*) emissions embodied in the final exports of country *s* to country *r*. The second term, $(F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr})$, is the importer's emissions embodied in the intermediate exports of country *s* to country *r*, which are then used by country *r* to produce its domestic final goods and services. The third term, $(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# Y^{sr}$, is foreign emissions from third countries *t* embodied in the final exports of country *s* to country *r*. The last term, $(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# (A^{sr} L^{rr} Y^{rr})$, is foreign emissions from third country *t* embodied in the intermediate exports of country *s* to country *r*, which are then used by country *r* as inputs to produce its domestic final goods and services.

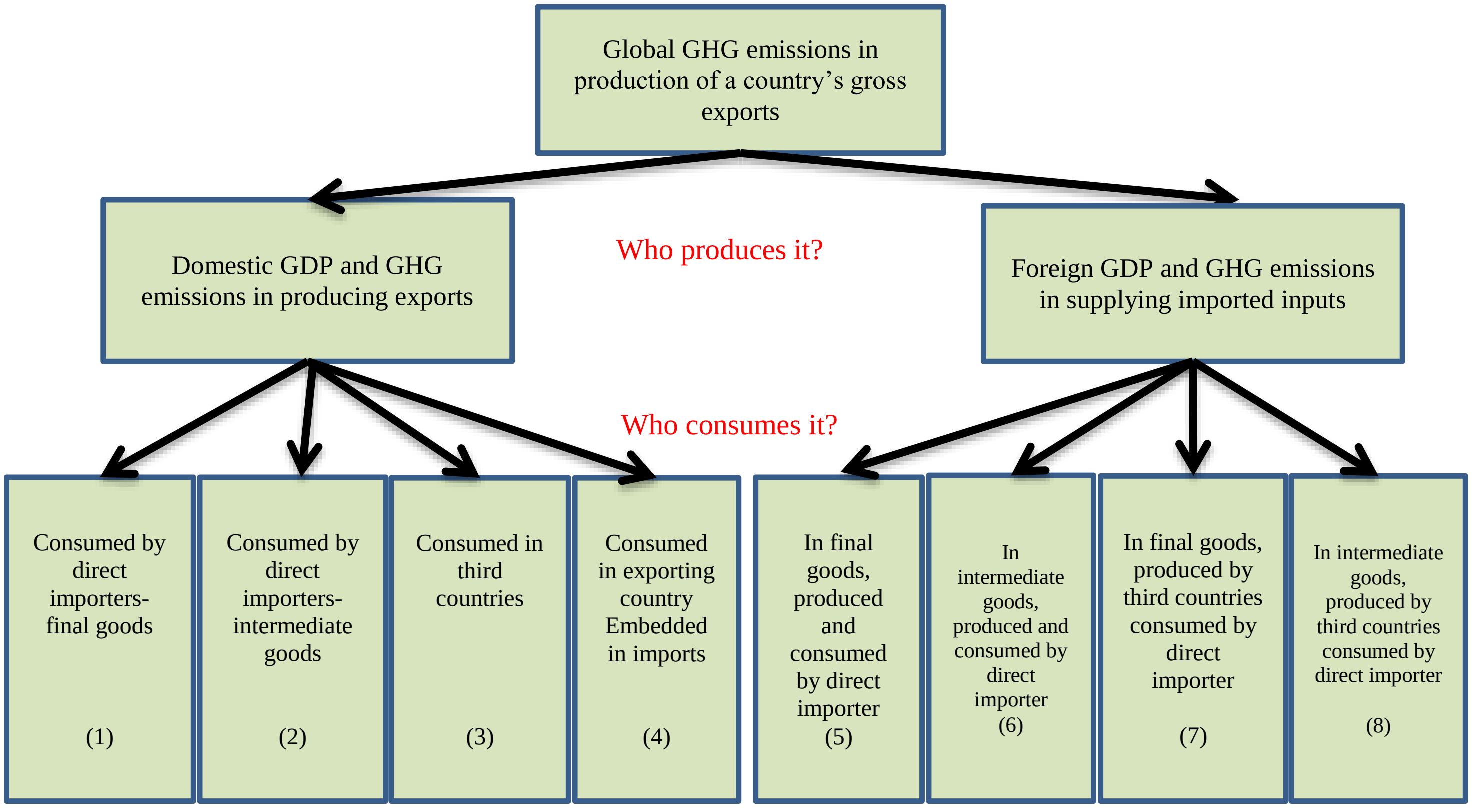
Combining equations (23), (26) and (28), we decompose the total global emissions generated from the production of a country's gross exports to its trading partner as

$$
\begin{aligned}
P(E^{sr}) &= \underbrace{(F^s B^{ss})^T \# Y^{sr}}_{(1)} + \underbrace{(F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr})}_{(2)} \\
&+ \underbrace{(F^s L^{ss})^T \# \left\{ (A^{sr} B^{rr} \sum_{t \neq s,r}^{G} Y^{rt}) + (A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{tt}) + (A^{sr} \sum_{t \neq s,r}^{G} \sum_{u \neq s,t}^{G} B^{rt} Y^{tu}) \right\}}_{(3)} + \underbrace{(F^s L^{ss})^T \# A^{sr} \sum_{t}^{G} B^{rt} Y^{ts}}_{(4)} \qquad (29) \\
&+ \underbrace{(F^r B^{rs})^T \# Y^{sr}}_{(5)} + \underbrace{(F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr})}_{(6)} + \underbrace{(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# Y^{sr}}_{(7)} + \underbrace{(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# (A^{sr} L^{rr} Y^{rr})}_{(8)}
\end{aligned}
$$

The first four terms of equation (29) represent emissions within the exporting country, which are a by-product of generating the exporting country's GDP; the last four terms in equation (29) represent emissions within foreign countries that provide intermediate inputs for the exporting country, but also create GDP for these foreign countries. The decomposition made in equation (29) is also shown in Figure 3.The number in the lowest level box corresponds to the terms in equation (29).

It turns out that separating emissions by backward versus forward industrial linkages is crucial to properly tracing emissions in trade at a disaggregated level. To our knowledge, the literature on embodied emissions in trade has not previously made a clear distinction between them. While Peters et al. (2011) made a distinction between emissions embedded in bilateral trade (EEBT) versus embodied emissions of final consumption, they do so only at the country aggregate level. More importantly, they do not distinguish backward from forward industrial linkages—such a distinction is not important at the country aggregate level, but is crucial at a disaggregated level (e.g., Peters and Hertwich 2006). In particular, quantifying emissions via backward linkages is crucial to measure gross trade related emissions at the sector, bilateral, or bilateral sector levels. Therefore, a key contribution of this paper is to systematically develop these quantitative emissions trade measures at both aggregated and disaggregated levels. This will facilitate the empirical understanding of carbon leakage at the sector and supply chain levels and provide useful insights regarding the role of trade in decarbonizing the global supply chain and the design of an integrated climate-trade policy to support it.

Figure 3 Global GHG emissions in the production of gross exports – backward industrial-linkage-based decomposition



2.5 Relationships among different emissions trade measures

The relationships among these different emissions trade measures can be summarized as follows.

In a world of three or more countries, domestic emissions generated by the production of bilateral gross exports to satisfy foreign final demand (EEX), forward linkage-based emissions exports (EEX_F), and backward linkage-based emissions exports (EEX_B) are, in general, not equal to each other at the bilateral/sector level, though they are the same at the country aggregate level. EEX_F and EEX_B are also equal at the bilateral aggregate level, while EEX and EEX_B are the same at the country/sector level.

EEG_F and (EEX_F + REE_F) are equal to each other at both country sector and country aggregate levels, but not equal at the bilateral sector level; while EEG_B and (EEX_B+ REE_B) are equal to each other only at the country aggregate level. Because both REE_F and REE_B are non-negative, EEG_F is always greater than or equal to EEX_F at country/sector level; both EEG_F and EEG_B are always greater than or equal to all the three measures of trade in embodied emissions (EEX, EEX_F and EEX_B) at the country aggregate level. While at the bilateral sector level, EEG (EEBT) measures can greater or smaller than EEX measures, as discussed in detail by Peters (2008). Finally, EEX_F and EEG_F as well as (EEX_F+REE_F) are always less than or equal to the sector-level total emission production $P(y_i^s)$.

The intuition behind these statements is simple: since direct emissions exports at the sector level are the same for all three trade-in-emissions measures, only indirect emissions trades may differ. However, because such indirect emissions exports are part of the total emissions produced by each sector, the total emissions in a country/sector set an upper bound for forward linkage-based emissions exports and domestic emissions embedded in gross exports.

The definition of the measures discussed in this section and their relationships are summarized in Tables 1a and 1b below.

Table 1a Definition of different measures of embodied emissions in trade

Acronym or label	**Definition in words**	**Key characters**	**Equation # in text**
EEX_F	Embodied emissions exports, forward-linkage-based	1. Emissions generated in producing goods and services that satisfy foreign final demand; 2. Include indirect emissions exports ; 3. Excluding emissions associate with intermediate exports that are returned and absorbed at home 4. Trade concepts, produced in one country, consumed by another.	**17**
EEX_B	Embodied emissions exports, backward linkage –based		**24**
EEX	Embodied emissions associated to gross bilateral trade flows		**23**
REE_F	Embodied emissions return home, forward linkage–based	Emissions generated by producing intermediate inputs exported to other countries, which eventually returns home via imports to satisfy domestic final demand	**18**
REE_B	Embodied emissions return home, backward linkage–based		**26**
EEG_F	Emissions embodied in a country's gross exports, forward linkage-based	1. Production concept, consistent to GDP by industry statistics 2. Focuses only on where the emissions are produced 3. Include the part of emissions that is generated by producing intermediate inputs for other countries but eventually re-imported	**19**
EEG_B	Emissions embodied in a country's gross exports, backward-linkage-based		**25**

Table 1b Relationships among different measures of embodied emissions in trade

	Aggregation level	EEX & EEX_F	EEX & EEX_B	EEX_F & EEX_B	REE_F & REE_B	EEG_F & EEG_B	EEG_F & (EEX_F+ REE_F)	EEG_B & (EEX_B+ REE_B)
e_i^{sr}	Bilateral-Sector	$\neq$	$\neq$	$\neq$	$\neq$	$\neq$	$\neq$	$\neq$
$\sum_{i=1}^{N} e_i^{sr}$	Bilateral Aggregate	$\neq$	$\neq$	$=$	$=$	$=$	$\neq$	$\neq$
$\sum_{r\neq s}^{G} e_i^{sr}$	Country-Sector	$\neq$	$=$	$\neq$	$\neq$	$\neq$	$=$	$\neq$
$\sum_{r\neq s}^{G}\sum_{i=1}^{N} e_i^{sr}$	Country Aggregate	$=$	$=$	$=$	$=$	$=$	$=$	$=$

3. Empirical analysis

Following the concepts and accounting framework proposed above, this section uses the WIOD[14] to demonstrate how this framework can help to gain a deeper understanding of the relationships between GVCs and CO_2 emissions from different perspectives. While we focus on CO_2 here, the framework works in the same way for any environmental stressor.

3.1 Tracing CO_2 emissions in GVCs at the national level

We first show how the accounting framework works with real world data at the national level as concepts summarized in Figures 1, 2, and 3.

Figure 4 shows "who produced CO_2 emissions for whom" by different GVC routes in 2009, using the two largest emitters, China and the US, as an example. This figure follows the forward industrial-linkage-based downstream decomposition method (Figure 1). Clearly, most CO_2 emissions (EH_F) are the result of satisfying the domestic final demand in each country without depending on international trade. This result holds for most large economies since the self-sufficient portion normally accounts for the largest part of total final demand. However, compared to the US, this portion is much lower in China. More than 30% of China's CO_2 emissions are induced by foreign final demand (EEX_F=EEX_F1+EEX_F2+EEX_F3). This is mainly for two

[14] www.wiod.org

reasons: 1) after China's accession to the WTO, foreign final demand has played an increasing role in driving the growth of China's GDP and the generation of China's CO_2 emissions (Peters et al. 2011); 2) the CO_2 emission intensity for producing one unit GDP in China is higher than that in the US (Davis and Caldiera 2010) (also see Appendix B4).

As we discussed in section 2, part of the CO_2 emissions induced by domestic final demand depend on international trade due to production sharing between home and foreign countries, measured by REE_F. As an example, producing a car in China to satisfy China's own final demand may require the importation of an engine from the US, which may use Chinese metal parts as inputs in its production. As a result, China's final demand for its domestic final products may cause its own CO_2 emissions to rise through the two-way international trade in intermediate goods and services. The forward industrial-linkage-based downstream decomposition method can also be used to trace foreign final demand in driving home-country produced CO_2 emissions by different GVC routes. As also shown in Figure 4, the share of CO_2 emissions induced by foreign final demand through final goods trade (EEX_F1) for China is obviously larger than that for the US. This depends on both the CO_2 emission intensity and how a country participates in GVCs. Most developing countries, such as China, join GVCs through exporting relatively large amounts of final products in their early stage of development.

Figure 4 Who produces emissions for whom (forward industrial-linkage-based decomposition, 2009)

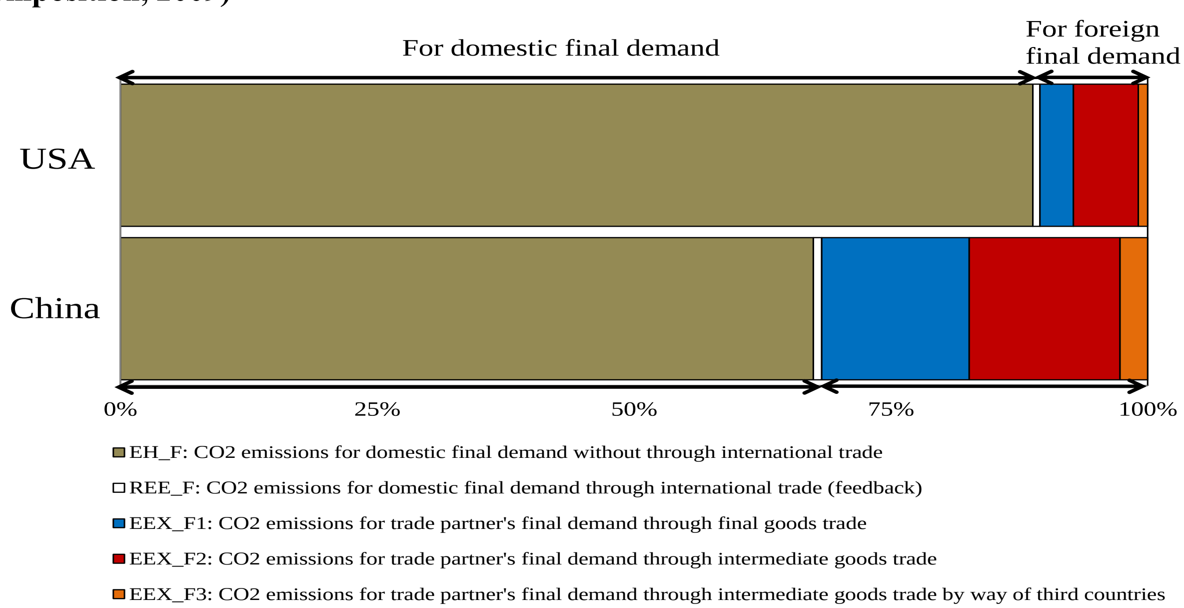


Figure 5 uses Germany and China as an example to show how CO_2 emissions are generated in GVCs by different emission sources when these two countries produce final goods and services. This figure follows the backward industrial-linkage-based upstream decomposition method (Figure 2). The foreign emissions induced by the production of final goods and services in Germany account for a relatively large share (more than 35% in 2009) compared to that in China (less than 10% in 2009). This depends not only on all related countries' CO_2 emission intensities, but also their cross country production sharing arrangements and the way they participate in GVCs. China's CO_2 emission intensity is higher than that of Germany (see Appendix B4); this makes China's domestic emissions take a relatively large share in the production of final goods. On the other hand, Germany's value chain has a relatively large foreign segment (relative to China, a country which is less integrated into the European Union), so more emissions may occur in other countries due to the induced demand for intermediate imports used for producing German-made final products.

In addition to technological efficiency, the CO_2 emission intensity may also depend on the structure of energy use. It's easy to see that the usage of coal accounts for a very large portion in China's domestic emissions when producing final goods and services, which is obviously different from that in Germany. In general, this indicator can help us clearly understand how a country's production of final goods and services impact on the CO_2 emissions in its upstream countries or industries (domestic or foreign) through various GVC routes.

Figure 5 Induced emissions in both domestic and international segments of GVC when a country produces final goods and services (backward industrial-linkage-based decomposition, 2009)

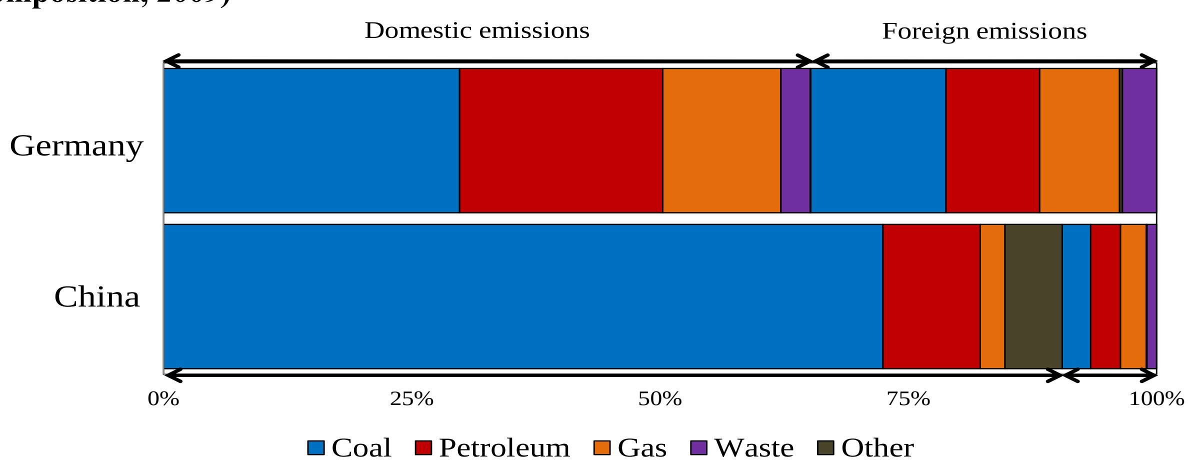
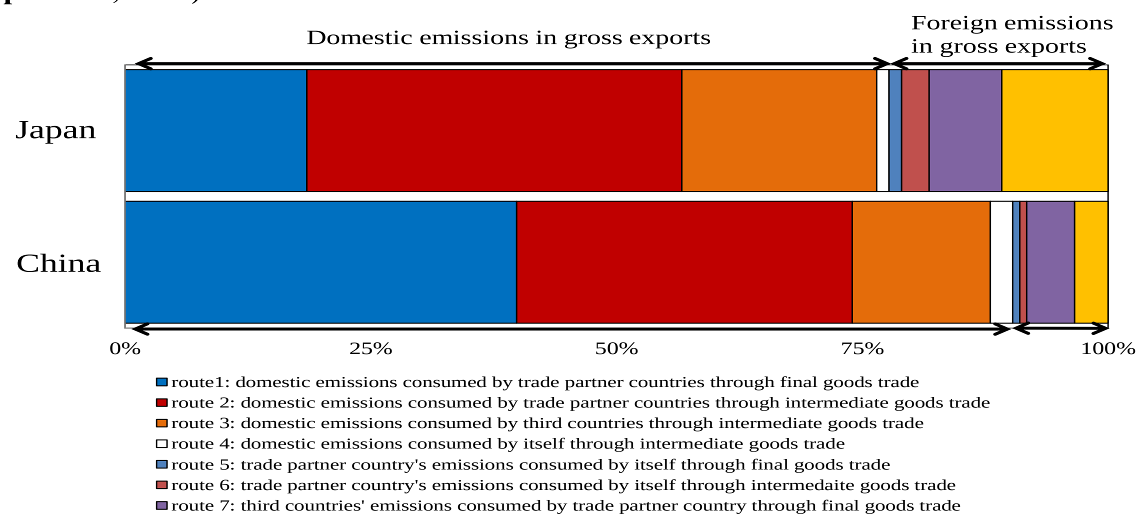


Figure 6 shows how Japan and China's gross exports generate both domestic and foreign CO_2 emissions by different GVC routes in 2009 (cf. Davis and Caldiera 2010). This figure corresponds to the backward industrial-linkage-based decomposition of gross exports (Figure 3). Compared to Japan, domestic CO_2 emissions generated from China's gross exports production account for a relatively large share (more than 90%). Though China imports more intermediate inputs than Japan does in producing gross exports, lower energy efficiency and high carbon intensity are considered the main drivers that increase China's domestic emissions share in gross exports. When looking at the domestic CO_2 emissions by GVC routes, a remarkable difference between Japan and China can be observed: Japan's domestic CO_2 emissions in gross exports are mainly generated in the production of intermediate goods and services that are exported to its trading partners, while, for China, final goods exports play a dominant role. This depends on both the way a country participates in GVCs and its CO_2 emission intensity. As a result of its comparative advantage in assembly, exports final products is one of the major ways that China participants GVCs. While Japan participates in GVCs largely through high-tech intermediate exports as a result of its comparative advantage in capital and skill intensive activities. Though the major exports with high comparative advantage for China are textile and electrical products which may not emit a large amount of CO_2 in their production processes, massive domestic intermediate inputs such as high-carbon electricity and chemicals are directly and indirectly embodied in these final product exports. As a result, domestic CO_2 emissions through final goods trade in China accounts for a relatively large share of its total emissions induced by gross exports.

Figure 6 Emissions embodied in gross exports (backward industrial-linkage-based decomposition, 2009)



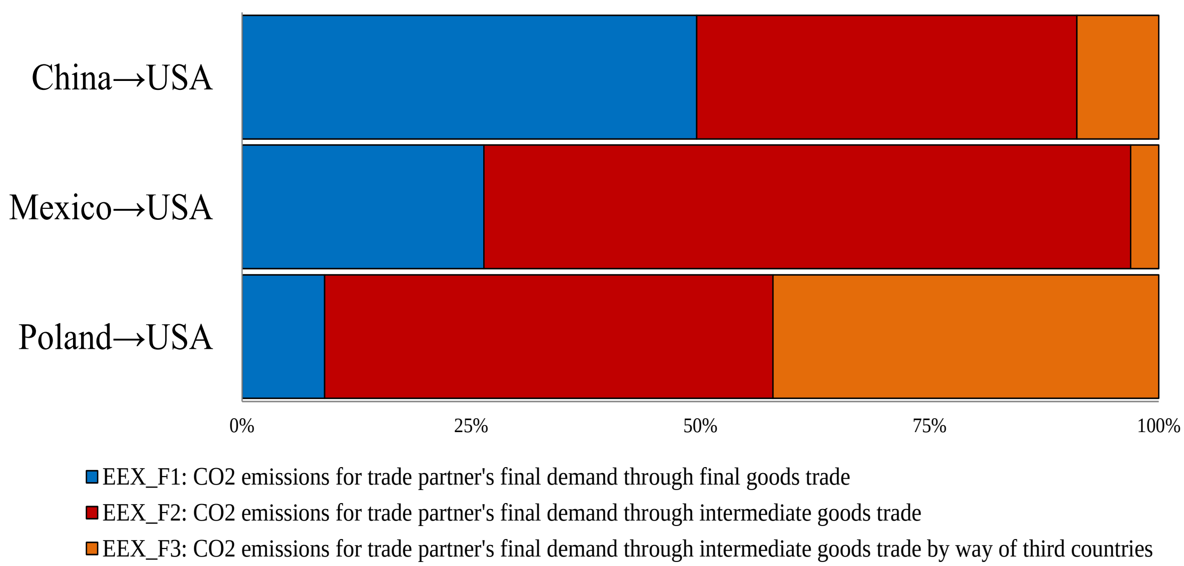
The share of foreign CO_2 emissions in a country's gross exports also depends on its trading partners' CO_2 emission intensities. Japan's import content in exports is lower than that of China, but its foreign emissions in gross exports are higher. This implies that relatively high foreign carbon intensity goods are embodied in Japan's gross exports. In addition, one important advantage of using this framework is that we can easily understand who produces gross exports and CO_2 emissions for whose consumption through which specific GVC route. For example, about 20% of CO_2 emissions in Japan's gross exports is for satisfying its direct trading partner's final demand, but this is emitted in third countries through Japan's use of third countries' intermediate goods and services to produce its exports to the partner country (route 7 and 8). Given the rapid extension of international fragmentation of production, this type of emissions in international trade tends to increase if no global treaty is in place. We report more detailed results on CO_2 emissions based on the 3 type decomposition method discussed in section 2 at the national level for the years between 1995 and 2009 in Appendix B1- B3.

3.2 Tracing CO_2 emissions in GVCs at the bilateral and sectoral levels

As discussed in section 2, the unified accounting framework proposed in this paper can also be used to trace CO_2 emissions in GVCs at detailed bilateral and sectoral levels. Figure 7 shows how emissions are generated in the CO_2 intensive metal industry in three selected countries, China, Mexico, and Poland, to satisfy US final demand through different GVC routes. This figure corresponds to Figure 1 following the forward industrial-linkage-based decomposition method. We use these three countries as an example here because they are all active players in GVCs of metal products and are also important direct or indirect trading partners of the US, while being located in three different continents: North America, Asia, and Europe. In addition, for most countries, the metal industry is always one of the largest emitters, with relatively high carbon intensity.

Figure 7 shows the CO_2 emissions in the metal industries in these three countries from activities to satisfy US's final demand via different GVC routes. The pattern is mainly determined by a country's position and participation in GVCs. China exports large quantities of final products to the US, so we see China's metal industry's CO_2 emissions from satisfying US's final demand arising mainly through final goods trade. Mexico is also close to the US consumer but unlike China, it is located in a relative upstream position in GVCs: it is one of the largest providers of parts and components of metal products to the US, for example, for the US auto industry. As a result, the CO_2 emissions in Mexico's metal industry are mainly embodied in its export of intermediate goods which are directly and indirectly consumed in the US. Poland is much further from the US consumers and is embedded in the EU economy, so it is located far upstream in the GVCs of metal products. Therefore, a large portion of Poland's metal industry CO_2 emissions are embodied in goods traded with third countries, such as metal products used in a German car finally consumed in the US. Tracing CO_2 emissions at the bilateral and sector levels as this example can help us to better understand the effect of a country's position and participation in GVC on the geographic source of its CO_2 emissions at industry level.

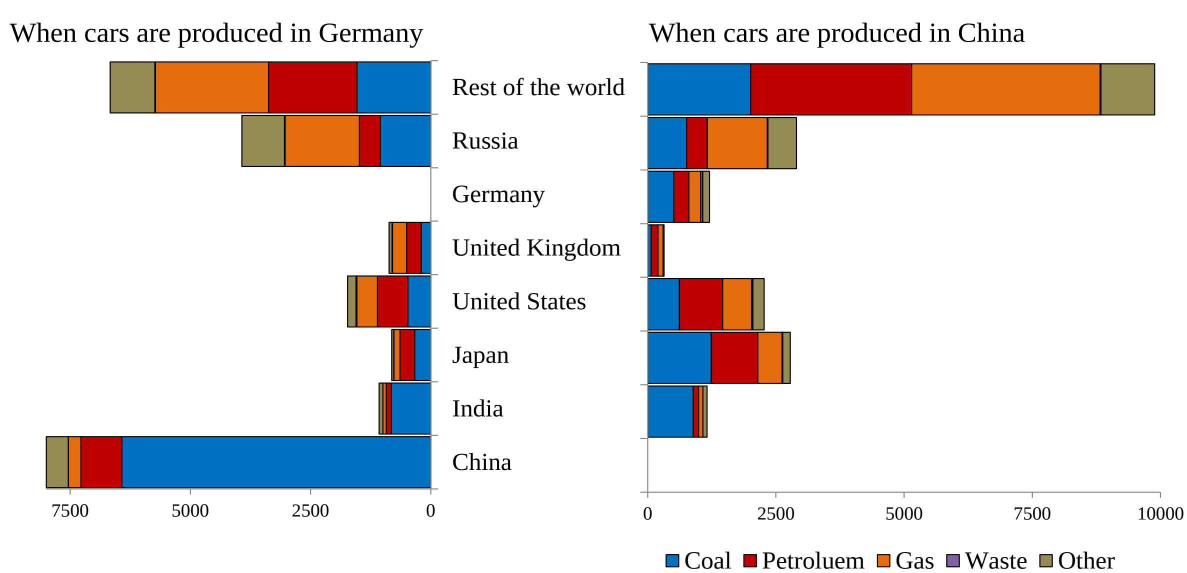
Figure 7 Metal industry's CO_2 emissions exports from selected countries to the US by different GVC routes (forward industrial-linkage-based decomposition, 2009)



Following the accounting method summarized in Figure 2, we use German-made and Chinese-made cars as an example to demonstrate how these two large car producers cause upstream CO_2 emissions in automobile GVCs. Figure 8 shows China, the rest of the world (RoW), and Russia are the economies most affected by car production in Germany, besides Germany itself. On the one hand, this is because these three economies are located upstream of Germany's car value chain through providing intermediate goods and services directly or indirectly for German car production. On the other hand, it is a result of the relatively high carbon intensity for producing intermediate goods in these countries compared to other upstream countries, like the US and Japan.

Another important factor is that different upstream countries involved in Germany's car value chain rely on different energy sources to produce their intermediate exports. For instance, China mainly relies on coal-based energy, hence coal-based CO_2 emissions account for the majority of emissions in China resulting from car production in Germany. Compared to the German-made car, the production activities of auto makers in China have a larger impact on CO_2 emissions in the RoW and Russia. China overtook the US, becoming the world's top auto maker and market in 2009[15]. Large amounts of components are imported from the RoW through various GVC routes directly and indirectly. As a result, the RoW has been the most affected upstream region in the production of Chinese-made cars. In addition, Japan and the US are also heavily affected since both countries are located in the upstream of China's car value chain by providing high-tech intermediate goods and services. This is different from the cars made in Germany because Germany obtains almost all high-tech parts from its domestic suppliers rather than its main rivals, the US and Japan.

Figure 8 Induced foreign CO_2 emissions from producing cars in selected countries (backward industrial-linkage-based decomposition)



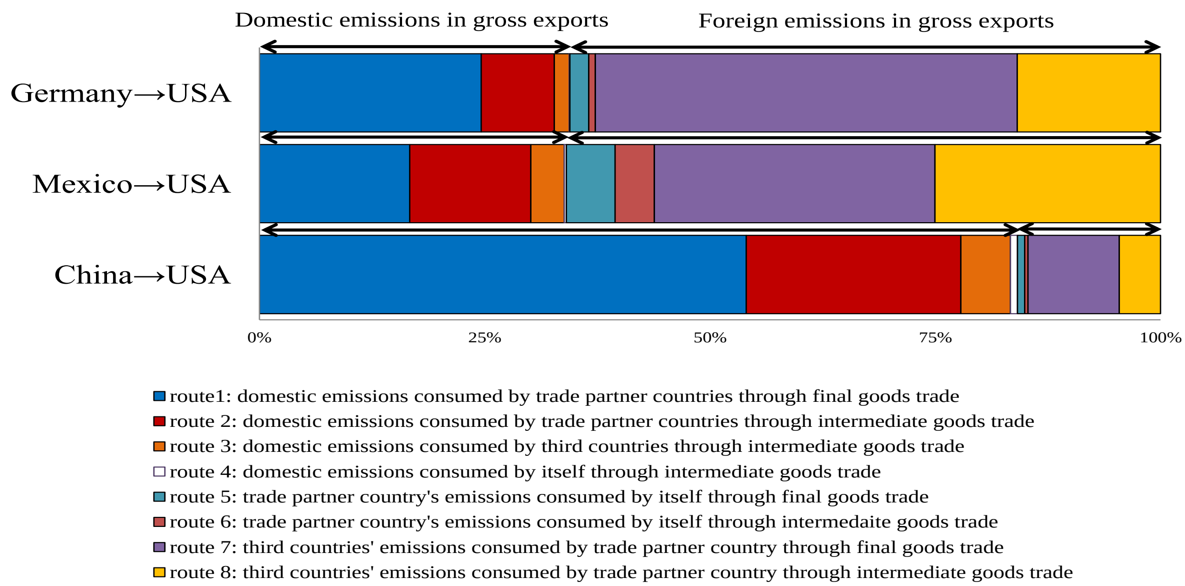
To illustrate how the accounting framework proposed in Figure 3 works at bilateral and

[15] China Daily, http://www.chinadaily.com.cn/bizchina/2010-01/12/content_9309129.htm, Updated: 2010-01-12 15:37

sector level, we use Germany, Mexico and China's electrical product exports to the US as an example. Figure 9 demonstrates how a country's gross exports of electrical products to the US generate both domestic and foreign CO_2 emissions through different GVC routes. These three countries were the largest trading partners for electrical products with the US in Europe, North America and Asia, respectively, in 2009. Figure 9 shows that about 85% of CO_2 emissions generated by China's gross exports of electrical goods to the US are emitted inside China, a very large portion of which is from the production of final goods exported to the US. Compared to China, Germany and Mexico show a very different pattern. Their exports of electrical product to the US induce more foreign CO_2 emissions. This difference is caused by several reasons that may operate in opposing directions: a higher domestic carbon intensity in producing goods and services leads to a larger portion of domestic emissions; a higher proportion of foreign intermediate imports in a country's exports (implying a higher participation in GVCs), leads to a smaller portion of domestic emissions.

Estimates based on WIOD shows that the import contents of electrical product exports to the US are 24%, 53% and 32% for Germany, Mexico and China, respectively. Germany's import contents are the lowest of these three exporting countries, but its gross exports to the US generate more foreign CO_2 emissions. This clearly reflects two factors. First, Germany has relatively low carbon intensity in producing exports. Second, Germany may import more high-carbon intensity intermediate goods directly or indirectly from other countries for producing its gross exports to the US. Mexico's imported content in its exports is the highest. This naturally leads to a large portion of foreign CO_2 emissions in its gross exports. The US's CO_2 emissions generated by gross exports of electrical products from Mexico to the US accounts for a very large portion (routes 5 and 6) compared to that in other countries. This is mainly because Mexico needs more intermediate parts and components provided by the US directly or indirectly when producing electrical products for exporting back to the US. In addition, this accounting framework can not only identify who produces gross exports and CO_2 emissions, but also help to identify who finally consumes the CO_2 emissions embodied in the gross exports. Clearly, the embodied CO_2 emissions in routes 1, 2, 5, 6, 7, and 8 are finally consumed by the US; emissions in route 3 are finally consumed by third countries, emissions in route 4 are finally consumed by the exporting countries themselves.

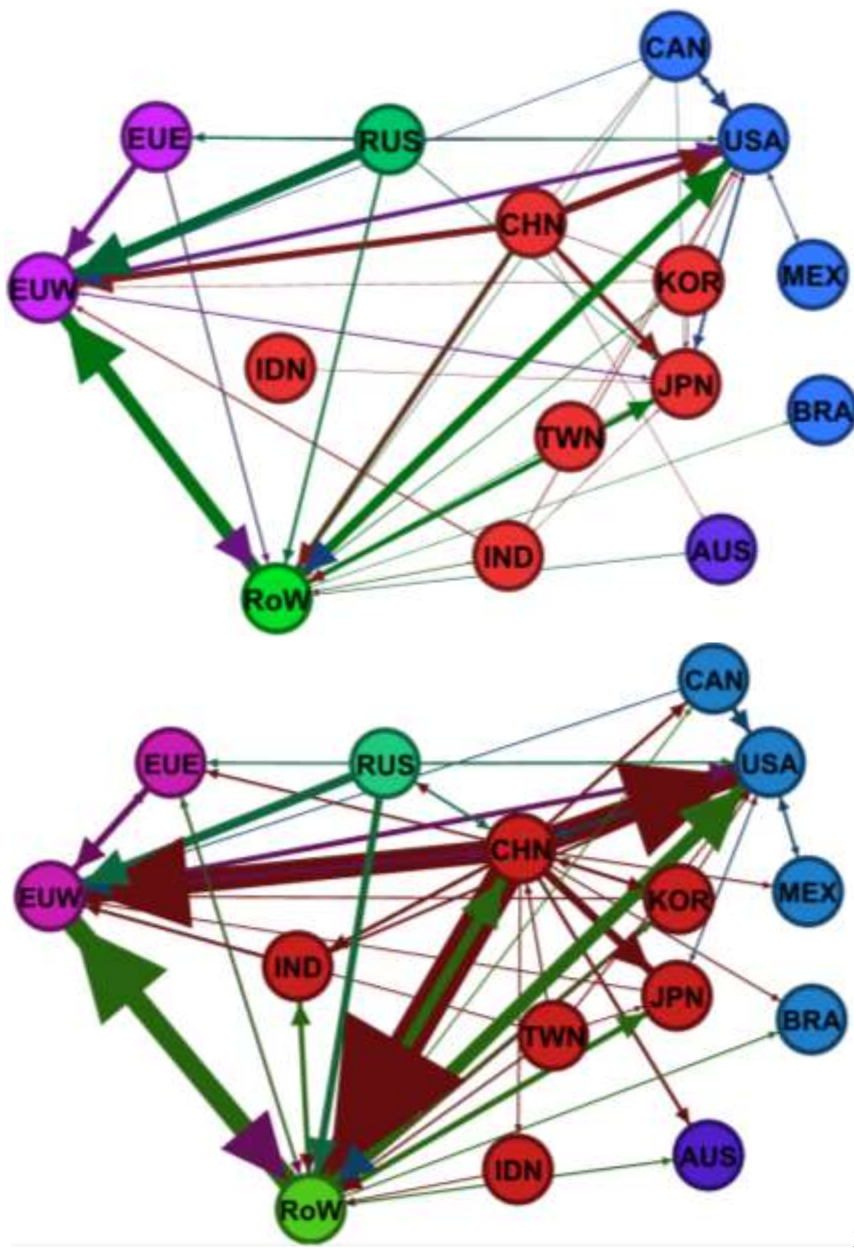
Figure 9 CO_2 emissions embodied in selected countries' gross exports of electrical product to the US (backward industrial-linkage-based decomposition, 2009)



3.3 Bilateral Trade in CO_2 Emissions

As illustrated in Table 1b, at the bilateral-aggregate and country-aggregate level, there is no difference between the forward and backward industrial-linkage-based embodied emissions exports measures. To simplify the concept, CO_2 emissions export from country A to B can be defined as country A's total CO_2 emissions induced by its partner country B's final demand (emissions generated by production in A, but the produced goods and services are absorbed in B). Figure 10 shows the bilateral trade in CO_2 emissions across the 15 largest countries or country groups for 1995 and 2009. In 1995, China, the US, EUW (the EU15), Russia and the RoW are the major exporters of CO_2 emissions; Japan, the US, the EUW and the RoW are the major importers of CO_2 emissions. The basic direction of bilateral flows remains unchanged between 1995 and 2009, but some interesting changes in the magnitude of CO_2 emissions trade can be observed. For example, China's exports of CO_2 emissions increased dramatically and, at the same time, China also became one of the largest importers of CO_2 emissions. More interesting thing is that the carbon emission trade between China and other developing countries has exceeded all bilateral emission trade between any developed economy blocks and China (the EU-China or the US-China). This is not only driven by the increased demand for Chinese manufacturing products from developing countries, but also due to "made in China" is highly depend on intermediate imports from other developing countries as inputs, and the RoW uses more and more intermediate imports from China, both of them have much higher carbon intensity than intermediate imports from developed countries. This could be a great concern since both China and countries in the RoW are Non-Annex B economies in Kyoto Protocol and both have relatively weak environmental regulations.

Figure 10 Bilateral trade in CO_2 emissions



1995

2009

Note: The magnitudes of emissions trade flows in this figure are based on EEX_F^{sr}. Exports from CHN (China) to the RoW (rest of the world) are respectively 104,563 Kt and 584,219 Kt for 1995 and 2009.

3.4 The relationship between GVC participation and embodied CO_2 emissions in gross exports

As mentioned in previous sections, a country's gross exports can generate both domestic and foreign CO_2 emissions through various GVC routes. The magnitudes of these two types of emissions highly depend on a country's position and participation in GVCs. The international economics literature on vertical specialization indicates that a country could participate GVCs in two ways: it can participate in GVCs from downstream, use imported intermediate inputs to produce exports, or from upstream, exports intermediate goods that are used as inputs by another country to produce goods for exports. To determine a county's position in a vertical integrated production chain need both measures (Koopman et. al. 2014). Figure 11a shows the relationship between a country's GVC participation from downstream (similar to Hummels et al. (2001)'s vertical specialization share indictor labeled as VS, measures the value of imported contents embodied in a country's exports) and its domestic share of total CO_2 emissions embodied in gross exports for the top 20 exporting economies in the world in 2009. The size of a bubble represents the magnitude of foreign CO_2 emissions embodied in a country's gross exports. The dark the color of the bubble, the higher the emission intensity (environment cost for per unit GDP; emissions in KT / GDP in million US$ at 1995 constant prices). The rings with different colors surrounding the bubbles show four different GVC routes (through energy, non-energy final goods trade, energy, non-energy intermediate goods trade). The main facts revealed by Figure 11a can be summarized as follows.

1. The higher the imported content in a country's exports, the smaller the domestic CO_2 emissions in its gross exports. When a country uses more foreign intermediate inputs to substitute for domestic inputs in producing exports, relatively less CO_2 emissions will be generated domestically[16]. The large scale of gross exports produced by China and the RoW and their relatively higher imported contents in exports compared to similar large countries, such as the US and Japan, cause more foreign CO_2 emissions. However, the relatively higher carbon intensity for developing economies, like China, India and the RoW, leads to a larger share of domestic CO_2 emissions embodied in their gross exports, although their shares of imported contents in exports are similar to some developed economies, such as Germany, France and Spain.

[16] Without considering the energy goods trade, the level of GVC participation for the RoW should be much lower.

2. Developing economies join GVCs by providing relatively more final goods, which is different from developed economies due to their different comparative advantages. For example, the foreign CO_2 emissions embodied in gross exports from the US, Japan, Korea and Taiwan are mainly as a result of intermediate goods trade, while for China, India and Mexico they are mainly as a result of final goods trade.
3. China and RoW have been the top two regions inducing massive foreign CO_2 emissions in producing exports. Besides their large scale of gross exports, both economies import high-carbon intensity components from each other. While Japan, Korea and Taiwan's bubbles are not only relatively large but also darker (higher carbon intensity). This is mainly because China has been their major trading partner, providing not just final goods but also intermediate goods.

Figure 11a The relationship between GVC participation and CO_2 emissions (2009)

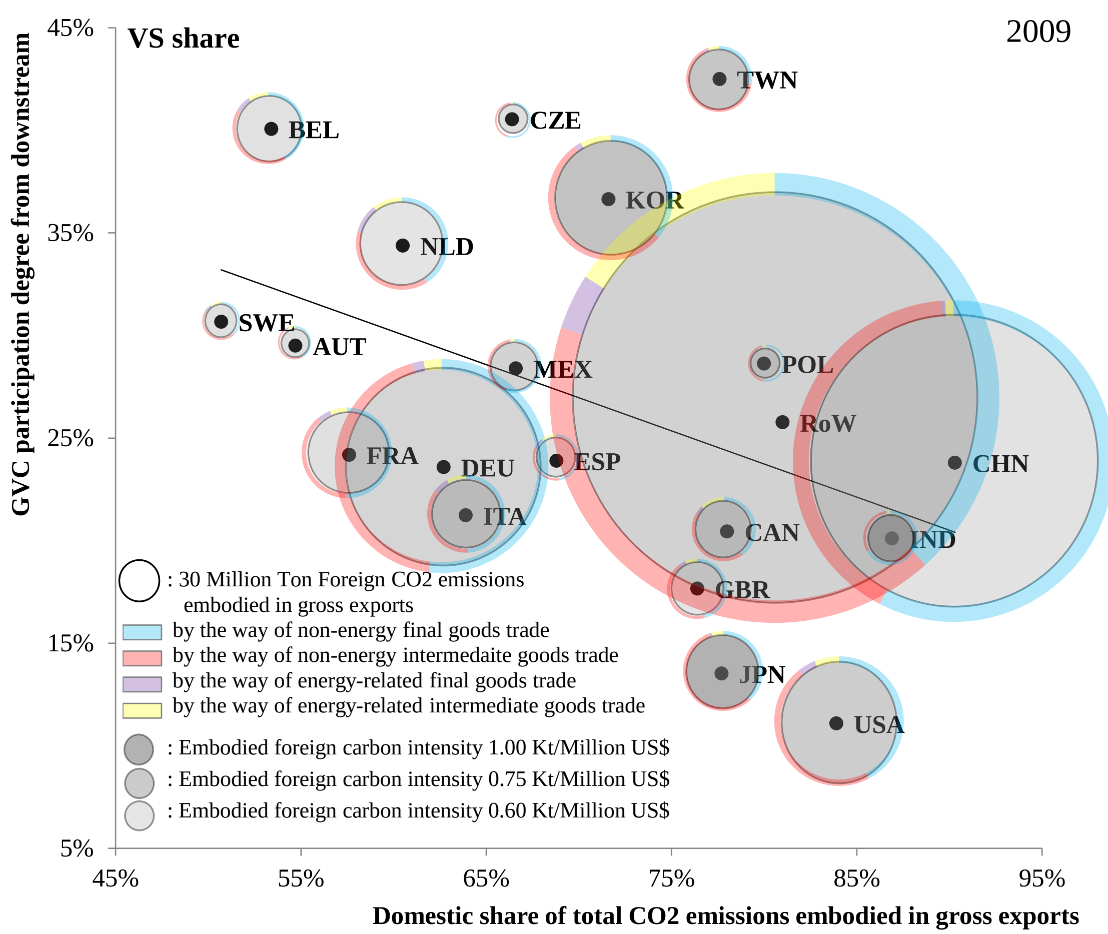
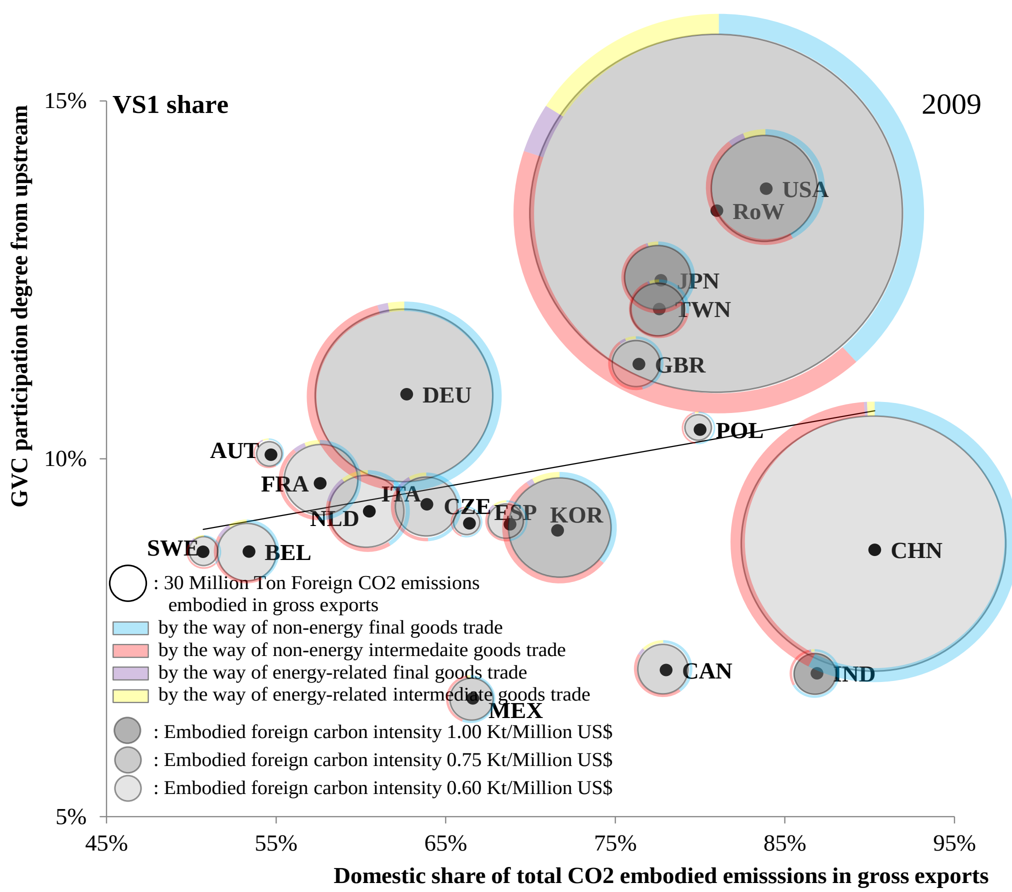


Figure 11b shows the relationship between a country's GVC participation from upstream (similar to Hummels et al. (2001)'s vertical specialization share indictor labeled as VS1, measures intermediate exports sent indirectly through other countries) and its domestic share of total CO_2 emissions embodied in gross exports. The horizontal axis remains no change, but countries' positions show very different pattern compared to that in Figure 11a. For example, because developed economies, such as the US, Japan, UK, Germany and Taiwan can provide more sophisticated manufacturing intermediates to their downstream countries for further processing and assembling, thus have higher degree of GVC participation from upstream, while India, Mexico and China have lower levels of participation. Viewing a country's participation from both upstream and downstream perspective provide more insights on the relationship between GVC participation and emissions in trade. For instance, Korea and Taiwan's positions are very close in Figure 11a, but very different in Figure 11b.

Figure 11b The relationship between GVC participation and CO_2 emissions (2009)



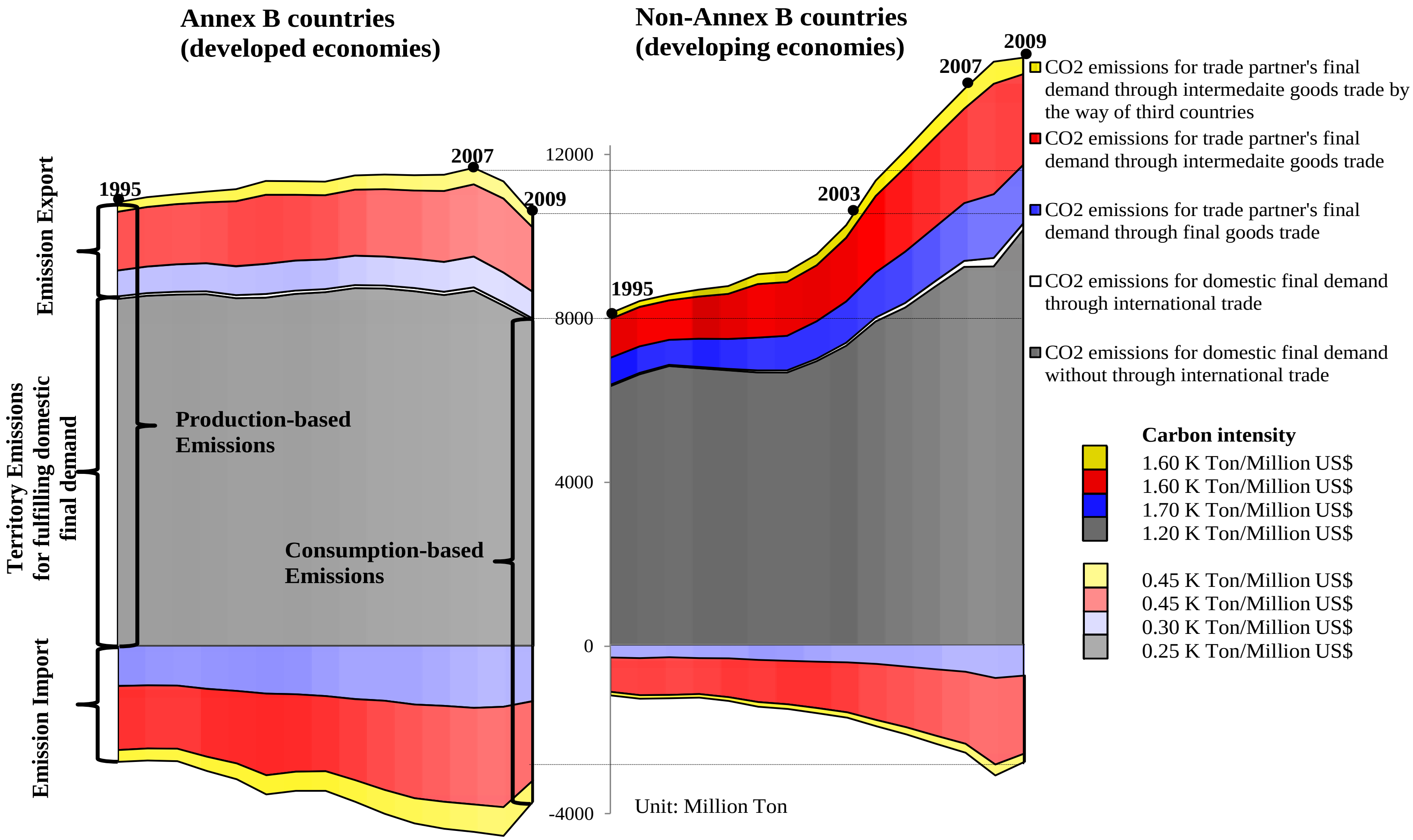
3.5 Consumption-based versus production-based CO_2 emissions and emissions transfer through different GVC routes

As pointed by Peters et al. (2011), most developed countries (as Annex B countries in the Kyoto Protocol) have increased their consumption-based CO_2 emissions faster than their territorial emissions. The net emissions transfer via international trade from developing to developed countries increased very rapidly and exceeds the Kyoto Protocol emissions reduction. Expanding on Peters et al. (2011) (use the forward industrial-linkage-based decomposition method summarized by Figure 1), we not only estimate the consumption-based and production-based emissions and their evolution from 1995 to 2009 for both Annex B and Non-Annex B country groups, but also further investigate how the international transfer of emissions occurs through various GVC routes with different carbon intensities.

Figure 12 shows that production-based CO_2 emissions for the Annex B country group have increased slightly in the period 1995-2009. Emissions exports for satisfying foreign final demands is the main driver of this increase, since territory emissions for fulfilling domestic final demands have shown a slight decrease in the same period. Consumption-based emissions for the Annex B country group experienced an increase due to increasing emissions imports (foreign emissions induced by Annex B countries). Looking at the structure of Annex B countries' increasing emissions trade by different GVC routes, we find that trade in intermediate goods is the main contributor to growth for both exports and imports, with little change in trade through final goods except for a slight increasing trend for imports. Compared to the Annex B countries, the Non-Annex B country group shows large increases in both domestic emissions and emissions trade. The production-based emissions for the Non-Annex B group in 2003 exceeded the Annex B group's peak level emissions (2007); Non-Annex B group's territory emissions for its domestic final demands in 2009 were close to the level of production-based emissions for Annex B groups. The Non-Annex B country group also imports more emissions and has been at the same level as the Annex B group's emissions exports.

With the information about carbon intensity (the dark the color, the higher the emission intensity with higher environment cost for per unit GDP; emissions in KT / GDP in million US$ at 1995 constant prices) along different GVC routes, the major facts observed from Figure 12 can be summarized as follows:

Figure 12 Consumption-based vs. production-based CO_2 emissions and emissions transfer through different GVC routes (1995-2009)



1. The environmental cost for generating one unit GDP in domestic production networks is lower than that through international trade for both developed and developing countries. The main driver is the high-carbon intensity trade in intermediates which has grown rapidly during the last 15 years.
2. The environmental cost for generating one unit GDP shows a decreasing trend for both Annex B and Non-Annex B counties from 1995 to 2009. However, the carbon intensity for Non-Annex B countries in 2009 is still higher than that for Annex B countries' 1995 level. In addition, the decrease on carbon intensity[17] in developing economies cannot offset the increased emissions from rapid economic and population growth. This clearly implies that helping more developing countries set carbon emission peak as China did last year is more urgent than decades ago.
3. The increasing complexity and sophistication in cross country production sharing also give an impetus to emissions transfer, since more cross-border CO_2 emissions transfer arises through intermediate goods trade via third countries.

3.6 The relationships among different measurements and their applications

As discussed in section 2, all the measures of embodied emissions proposed in the paper are consistent with the SNA standard. However, different measures provide different tools to quantify embodied CO_2 emissions trades from different perspectives[18]. To provide a better understanding of the differences between these measures and their economic and policy implications, we apply both forward and backward industrial-linkage-based decomposition to measure China's Released Comparative Advantage (RCA[19]).

The traditional RCA indicator (Balassa 1966) is based on gross exports. As pointed by Wang et al. (2013), the traditional RCA ignores both domestic production sharing and international

[17] For detailed empirical results on carbon intensity at the bilateral level by different energy types along GVCs, one can refer to Figure B3 in Appendix.

[18] Table B5 in Appendix B reports bilateral embodied emissions trade of Electrical and Optical Equipment (WIOD sector 14) between China and Japan in 2009 by different measures we defined in section 2 of this paper. It is a numerical example to illustrate the analytical relations among various emission trade measures we discussed in table 1b using real world data.

[19] The RCA indicator used in the paper follows the additional RCA measure proposed by Hoen and Oosterhaven (2006). This type of indicator ranks from -1 to +1, with a symmetric distribution that centers on a stable mean of zero, independent of the sector classifications used.

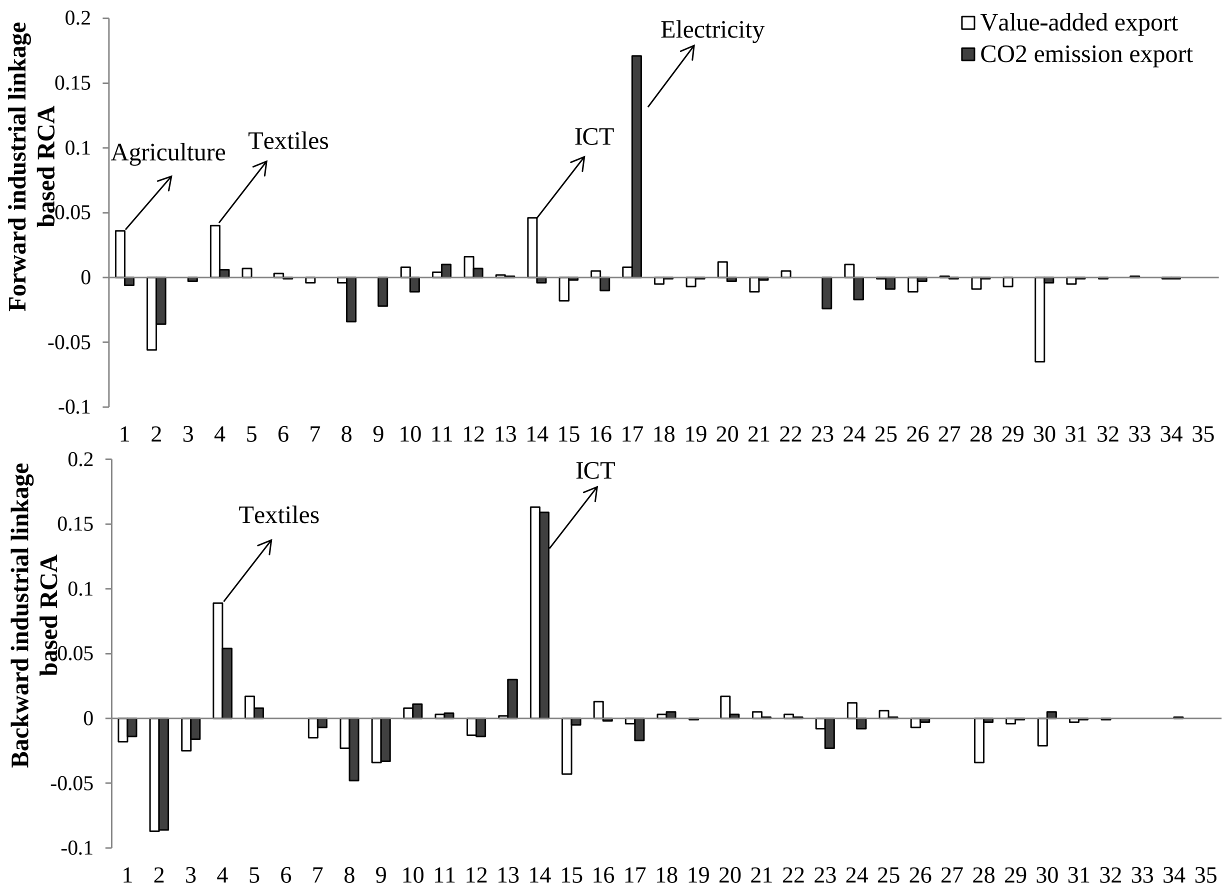
production sharing. A conceptually correct measure of comparative advantage needs to exclude foreign-originated value added and pure double counted terms in gross exports but include indirect exports of a sector's value added through other sectors of the exporting country. When a country uses imported intermediate goods intensively to produce for its exports, Koopman et al. (2014) show that RCA based on gross exports can be very misleading and suggested a way to remove the distortion of double counting by focusing on domestic value-added in exports. We follow the same idea here to measure a country's RCA by using both value-added exports and CO_2 emissions exports. As mentioned earlier, according to the forward industrial-linkage-based decomposition, a country's value-added or CO_2 emissions exports at the sector level represent how much of this country's specific sector's value-added or CO_2 emissions embodied in all downstream countries' and sectors' gross output is finally consumed in foreign countries. According to the backward industrial-linkage-based decomposition, a country's value-added or CO_2 emissions exports at the sectoral level measures how much this country's value-added or CO_2 emissions in all upstream production stages are embodied in a specific product that is finally consumed in foreign countries.

The upper penal of Figure 13 shows China's forward industrial linage based RCA by sector ranking for both value-added and CO_2 emissions exports. For value-added exports, Electrical and Optical Equipment (ICT, WIOD sector 14), Textiles and Textile Products (WIOD sector 4) and Agriculture, Hunting, Forestry and Fishing (WIOD sector 1) show the highest RCA since all these sectors generate more value-added for fulfilling foreign countries' final demand through global value chains directly and indirectly. However, for CO_2 emissions exports, only Electricity, Gas and Water Supply (sector 17) shows an extremely high RCA. This implies that energy sector emits large amounts of CO_2 emissions embodied in China's various exports of goods and services to satisfy foreign final demands, which are not show up in traditional trade statistics since there is a negligible amount of Chinese electricity exported directly.

The bottom penal of Figure 13 shows the backward industrial linkage based RCA estimates for China. Clearly, the RCA for value-added export is normally consistent to that for CO_2 emissions export at the sector level. Comparing both measures for China's Electricity, Gas and Water Supply sector, we see that from the perspective of a producer who makes Electrical products, the production process has a low-carbon intensity (forward), but from the viewpoint of foreign user, this product has a high-carbon intensity since relatively large shares of CO_2 emissions are generated in its upstream sectors (backward).

Both downstream-driven and upstream-driven RCA indicators have their own roles in helping better understanding the fact that, the competitiveness of Chinese manufacturing products in the world market is related to the cheaper cost of carbon emissions in China.

Figure 13 Backward vs. forward industrial linkage based RCA for both value-added exports and CO_2 emissions exports (2009)



4. Concluding remarks

The rise of global value chains has dramatically changed the nature and structure of international trade in recent decades. There is particularly strong growth in intermediate goods and services that may cross borders multiple times before the delivery of final products. It is difficult to understand “who produces value for whom” in a fragmented production system, compared to the relatively simple situation in the Ricardian era where exports were mainly final goods. The increasing complexity of GVCs has produced challenges for economic and environment policy as well as international governance. Therefore, it is important to understand to what extent GVCs impact on both value creation and emissions generation for trade and environment policies.

This paper unifies and extends existing emissions trade related measures, quantify their relationships, and further combines them with trade in value-added and GVC-based measures in recent literature into one consistent accounting framework, in which both value added and emissions can be systematically traced at country, bilateral, and sector levels through various GVC routes. In principle, when new countries or years are added to the WIOD database, or an alternative inter-country input-output table becomes available, our accounting framework can be applied as well. So the accounting framework developed in this paper is not inherently tied to the WIOD database and can be a stand-alone tool. It provides a useful analytical method for both trade and environment economists as well as policy makers to study the impact of production fragmentation and emergence of GVCs on the environment. We show that conventional analysis on carbon leakage, shared responsibilities and the environment cost of a country's comparative advantages can all benefit from applying such new analytical tool developed in this paper.

Better and detailed information that combine environment cost and economic benefit in each production stages and trade routes along GVCs provide scientific evidence for concrete and targeted incentive mechanism and greenhouse gas emission reduction policy design. We leave further analysis of the full decomposition results (it takes up 20 gigabytes of space) and link it to policy design for our future research agenda.

References

Andrew, R.M. and Peters, G.P. (2013). A multi-region input-output table based on the Global Trade Analysis Project Database (GTAP-MRIO). *Economic Systems Research* 25 (1): 99-121.

Antràs, P. and Chor, D. (2013). Organizing the global value chain. *Econometrica*, 81(6): 2127-2204.

Arto, I. and Dietzenbacher, E. (2014). Drivers of the growth in global greenhouse gas emissions. *Environmental Science & Technology* 48(10): 5388−5394.

Atkinson, G., Hamilton, K., Ruta, G., Mensbrugghe, D. van der (2011). Trade in ‘virtual carbon’: Empirical results and implications for policy. *Global Environmental Change* 21(2): 563-574.

Balassa, B. (1965). Trade Liberalization and Revealed Comparative Advantage. *the Manchester School*, 33 (2): 99-123.

Baldwin, R. (2012). WTO 2.0: Global governance of supply-chain trade. *CEPR Policy Insight* 64.

Baldwin, R. and Robert-Nicoud, F. (2014). Trade-in-goods and trade-in-tasks: An integrating framework. *Journal of International Economics* 92(1): 51-62.

Bastianoni, S., Pulselli, F.M., Tiezzi, E. (2004). The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics* 49: 253-257.

Cadarso, M.A., Lopez, L.A., Comez, N., Tobarra, M.A. (2012). International trade and shared environmental responsibility by sector. An application to the Spanish economy. *Ecological Economics* 83: 221-235.

Davis, S.J. and Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *PNAS* 107(12): 5687-5692.

Davis, S.J., Peters, G.P., and Caldeira, K. (2011). The supply chain of CO_2 Emissions. *PNAS* 108 (45): 18554-18559.

de Haan, M. and Keuning, S. J. (1996). Taking the environment into account: The NAMEA approach. *Review of Income and Wealth* 42: 131-148.

de Haan, M. and Keuning, S. J. (2001). The NAMEA as validation instrument for environmental macroeconomics. *Integrated Assessment* 2: 79-87.

Ferrarini, B. and D. Hummels, eds. (2014) *Asia and Global Production Networks –Implications for Trade, Incomes and economic Vulnerability*. Edward Elgar.

Feng, J.J. (2003) Allocating the responsibility of CO2 over-emissions from the perspectives of benefit principle and ecological deficit. *Ecological Economics* 46: 121-141.

Grossman, G.M., Rossi-Hansberg, E. (2008). Trading tasks: a simple theory of offshoring. *The American Economic Review* 98(5): 1978-1997.

Hertwich, E.G. and Peters, G.P. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science and Technology* 43 (16): 6414-6420.

Hoekstra, A. and Mekonnen, M. (2012). The water footprint of humanity, PANS, 109(9), 3232-3237.

Hoekstra, A. and Wiedmann, T. (2014). Humanity’s unsustainable environmental footprint. *Science* 344(6188): 1114-1117.

Hoen, A.R. and Oosteraven, J. (2006). On the measurement of comparative advantage. *The Annals of Regional Science* 40: 677-691.

Hummels, D., Ishii, J., Yi, K.M. (2001). The nature and growth of vertical specialization in world trade. *Journal of International Economics* 54 (1): 75-96.

Johnson, R. and Noguera, G. (2012). Accounting for Intermediates: Production Sharing and Trade in Value added. *Journal of International Economics* 86: 224-236.

Kanemoto, K., Lenzen, M., Peters, G.P., Moran, D., Geschke, A. (2012). Frameworks for comparing emissions associated with production, consumption, and international trade. *Environmental Science and Technology* 46: 172-179.

Kanemoto, K. Moran, D., Lenzen, M., Geschke, A. (2014). International trade undermines national emission reduction targets: New evidence from air pollution. *Global Environmental Change* 24: 52-59.

Koopman, R., Wang, Z., Wei, S.J. (2014). Tracing value-added and double counting in gross exports. *American Economic Review* 104(2): 459-494.

Lenzen, M., Moran, D, Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A. (2012), International trade drives biodiversity threats in developing nations. *Nature* 486: 109-112.

Lenzen, M., Murray, J., Sack, F., Wiedmann, T. (2007). Shared producer and consumer responsibility ‐ theory and practice. *Ecological Economics* 61: 27-42.

Leontief, W. (1936). Quantitative input and output relations in the economic system of the United States. *The Review of Economic and Statistics* 18: 105-25.

Lin, J., Pan, D., Davis, S.J., Zhang, Q., He, K., Wang, C., Streets, D.G., Wuebbles, D.J., Guan, D. (2014). China's international trade and air pollution in the United States. *PNAS* 111(5): 1736-1741.

Meng, B., Xue, J., Feng, K., Guan, D., Fu, X. (2013). China's inter-regional spillover of carbon emissions and domestic supply chains. *Energy Policy* 61: 1305-1321.

Miller, R.E., and Blair, P.D. (2009). *Input – Output Analysis: Foundations and Extensions*. (2nd ed.). New York: Cambridge University Press.

OECD, WTO and UNCTAD (2013) "Implications of Global Value Chains for Trade, Investment Development and Jobs" prepared by OECD, WTO and UNCTAD for the G20 Leaders Summit, St. Petersburg, Russian Federation September.

Pedersen, G.O. and de Haan, M. (2006). The system of environmental and economic accounts-2003 and the economic relevance of physical flow accounting. *Journal of Industrial Ecology* 10: 19-42.

Peters, G.P., and Hertwich, E.G. (2006). The importance of imports for household environmental impacts. *Journal of Industrial Ecology* 10 (3): 89-109.

Peters, G.P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics* 65: 13-23.

Peters, G.P. and Hertwich, E.G. (2008). CO2 embodied in international trade with implications for global climate policy. *Environmental Science and Technology*, 42 (5): 1401-1407.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *PANS* 108(21): 8903-8908.

Peters, G.P., Davis, S.J., Andrew, R. (2012). A synthesis of carbon in international trade. *Biogeosciences* 9: 3247–3276.

Rodrigues, J., Domingos, T., Giljum, S., Schneider, F. (2006). Designing an indicator of environmental responsibility. *Ecological Economics* 59: 256-266.

Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., de Vries,G.J. (2014a). The World Input-Output Database (WIOD): Contents, concepts and applications. *GGDC Research Memorandum* 144. Groningen Growth and Development Centre.

Timmer, M.P., Erumban, A.A., Los, B., Stehrer, R., De Vries, G.J., (2014b). Slicing up global value chains. *Journal of Economic Perspectives* 28(2): 99-118.

Timmer, M. P., Los, B., Stehrer, R. and de Vries, G. J. (2013). Fragmentation, incomes and jobs: an analysis of European competitiveness. *Economic Policy* 28(76): 613–661.

Tukker, A. and Dietzenbacher, E. (2013). Global multiregional input–output frameworks: An introduction and outlook. *Economic Systems Research* 25(1): 1-19.

Wang, Z., Wei, S.J., Zhu, K. (2013). Quantifying international production sharing at the bilateral and sector levels. *NBER Working Paper* 19677.

Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A. (2013). Affluence drives the global displacement of land use. *Global Environmental Change* 23(2): 433-438.

Wiedmanna, T.O., Schandlb, H. Lenzen, M., Moranc, D., Suh, S., West, J., Kanemoto, K. (2013). The material footprint of nations. *PANS.*

Yi, K.M. (2010). Can multistage production explain the Home Bias in trade?. *The American Economic Review* 100(1): 364-393.