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Tracing CO_2 Emissions in Global Value Chains

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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 production network routes. 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. Using this unified accounting method, we trace CO2 emissions in the global production and trade network among 41 economies in 35 sectors from 1995 to 2009, basing our calculations 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.

Keywords: Value-added, Embodied emissions, Global value chains, Input–output
JEL classification: E01, E16, F1, F14, F18, Q5, Q54, Q56

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Key Words: Value-added and embodied-emissions accounting, Global value chains and environment; input–output analysis; International trade

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Tracing CO_2 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. Studies on GVCs have focused on the creation and distribution of value added, employment, and income (OECD 2013; Timmer et al. 2013; Ferrarini and Hummels 2014). In recent years, however, many scholars have turned their attention to the interaction of GVCs and environmental policies (Wiedmann 2009; 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; Wiebe et al. 2012; Arto and Dietzenbacher 2014). The same conclusions have been reached for many environmental issues (Hoekstra and Wiedmann 2014), such as energy (Davis et al. 2011), air pollution (Lin et al. 2014; Kanemoto et al. 2014), material use (Bruckner et al. 2012; Wiedmann et al. 2013), land use (Meyfroidt et al. 2010; Weinzettel et al. 2013), biomass (Peters et al. 2012), water (Hoekstra and Mekonnen 2012), and biodiversity (Lenzen et al. 2012). This line of research has considerable methodological and conceptual overlap with the work on trade in value added (Koopman et al. 2014), 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 suppose 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 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 and from different perspectives along the GVCs. This paper aims to generalize all the existing measures related to embodied emissions in the literature, with the aim of providing a unified framework for tracing emissions in GVCs at the country, industry/product and bilateral levels.

This framework allows analysts to address policy-related questions such as the following:

1) What amount of emissions generated by a country's specific industry is for its own use and how much is for consumption by other countries and sectors?
2) How does a country's production of a specific final product induce emissions from other sectors and countries along global production network?
3) Who produces emissions for whom and by what route along GVCs in the production of gross exports?
4) What amounts of emissions have been generated to create one unit of GDP in each stage of production through various GVC routes?

In building a unified accounting framework, existing efforts toward the measurement of embodied emissions in trade, based on multi-regional input–output (IO) models, provide a good starting point (e.g., Ahmad and Wyckoff 2003; Lenzen et al. 2004; Peters 2008; Peters and Hertwich 2008a; Hertwich and Peters 2009; Kanemoto et al. 2012). These efforts have significantly enhanced our understanding of embodied emissions in trade, but they do not completely address all the questions listed above. This is because most of these previous efforts focus on measuring embodied emissions at the country level, and are often not able to provide both industry/product-level and bilateral-level solutions for capturing the embodied emissions in trade through both upstream and downstream supply chains.

In this paper, we first use a traditional two-country, two-sector multi-regional IO 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). Using the forward industrial-linkage-based decomposition, the total emissions from a country/industry can be traced according to where the produced final goods and services are consumed and from which downstream GVC routes they came. This is consistent with the production-based National Emission Inventory (NEI), which is conducted according to the economic activities of residential institutions as defined by the System of National Accounts (SNA). This provides information that is 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.

To answer questions 1) and 2) listed above, applying Leontief's original insight is sufficient. However, measuring global emissions generated by a country's gross exports and tracing its source structure (questions 3 and 4) requires extending Leontief's original method to decompose gross intermediate trade flows across countries according to their final absorption. To do this, 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. In addition, using the same accounting framework to simultaneously measure value added and emissions in trade helps us to better understand in detail the potential environmental cost of generating GDP along GVCs at country, industry/product, and bilateral levels.

The empirical part of the paper applies the integrated accounting frameworks described above to the World Input–Output Database (WIOD) for the years from 1995 to 2009 to develop a deeper understanding of the relationship between emissions and GVCs from various perspectives. Major findings of this research are summarized in the concluding section.

2. Concepts and Methodology

2.1 Embodied emissions through forward and backward industrial linkage

The methods used to estimate embodied emissions[1] 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

[1]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.

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 flows (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 consumption $A^{ss}X^s+A^{sr}X^r$ and final consumption $Y^{ss}+Y^{sr}$. The two-country production and trade system can be written as a multi-country IO (MRIO) model in block matrix notation

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

which shows a clear distinction between intermediate consumption (AX) and final consumption (Y). The intermediate consumption can be either used domestically (diagonals) or exported/imported (off-diagonals), and likewise for the final consumption. In this model, the final consumption is exogenous, while intermediate consumption 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 emission generated from the process of producing the \$1 of final products. Expressing this process mathematically using the terms defined above, we have

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

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

$$\begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} = \begin{bmatrix} a_{11}^{ss} & a_{12}^{ss} & a_{11}^{sr} & a_{12}^{sr} \\ a_{21}^{ss} & a_{22}^{ss} & a_{21}^{sr} & a_{22}^{sr} \\ a_{11}^{rs} & a_{12}^{rs} & a_{11}^{rr} & a_{12}^{rr} \\ a_{21}^{rs} & a_{22}^{rs} & a_{21}^{rr} & a_{22}^{rr} \end{bmatrix} \begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} + \begin{bmatrix} y_1^{ss} + y_1^{sr} \\ y_2^{ss} + y_2^{sr} \\ y_1^{rs} + y_1^{rr} \\ y_2^{rs} + y_2^{rr} \end{bmatrix} \quad (2a)^{3}$$

Domestic IO Coefficients

Import IO Coefficient

$$\begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} = \begin{bmatrix} 1 - a_{11}^{ss} & -a_{12}^{ss} & -a_{11}^{sr} & -a_{12}^{sr} \\ -a_{21}^{ss} & 1 - a_{22}^{ss} & -a_{21}^{sr} & -a_{22}^{sr} \\ -a_{11}^{rs} & -a_{12}^{rs} & 1 - a_{11}^{rr} & -a_{12}^{rr} \\ -a_{21}^{rs} & -a_{22}^{rs} & -a_{21}^{rr} & 1 - a_{22}^{rr} \end{bmatrix}^{-1} \begin{bmatrix} y_1^{ss} + y_1^{sr} \\ y_2^{ss} + y_2^{sr} \\ y_1^{rs} + y_1^{rr} \\ y_2^{rs} + y_2^{rr} \end{bmatrix},$$
$$= \begin{bmatrix} b_{11}^{ss} & b_{12}^{ss} & b_{11}^{sr} & b_{12}^{sr} \\ b_{21}^{ss} & b_{22}^{ss} & b_{21}^{sr} & b_{22}^{sr} \\ b_{11}^{rs} & b_{12}^{rs} & b_{11}^{rr} & b_{12}^{rr} \\ b_{21}^{rs} & b_{22}^{rs} & b_{21}^{rr} & b_{22}^{rr} \end{bmatrix} \begin{bmatrix} y_1^{ss} + y_1^{sr} \\ y_2^{ss} + y_2^{sr} \\ y_1^{rs} + y_1^{rr} \\ y_2^{rs} + y_2^{rr} \end{bmatrix} \quad (3a)$$

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

[3] 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.

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_{11}^{sr} is the direct IO coefficient that shows the intermediate goods required in sector 1 of country *s* that are used in the production of one unit of gross output in sector 1 of country *r*, and b_{11}^{ss} is the total requirement coefficient that gives the total amount of the gross output of sector 1 in country *s* needed to produce an extra unit of the sector 1 final product in country *s* (which is for consumption in both countries *s* and *r*). Other coefficients have similar economic interpretations.

We condense the final demand vector in (3a) as

$$\left[y_1^{ss}+y_1^{sr} \quad y_2^{ss}+y_2^{sr} \quad y_1^{rs}+y_1^{rr} \quad y_2^{rs}+y_2^{rr}\right]^T = \left[y_1^s \quad y_2^s \quad y_1^r \quad y_2^r\right]^T$$

and 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

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

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

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

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

which distributes the total emissions produced in a country/industry according to where its final goods and services are consumed. The value of p_j^s 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 Account (SNA), and is similar to GDP-by-industry statistics[4] (de Haan and Keuning 1996, 2001; Pedersen and de Haan 2006).

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 produce final products, and the third and fourth elements, $f_1^r b_{12}^{rs}(y_1^{ss} + y_1^{sr})$ 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*, that is,

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

where $p(y_1^s)$ denotes the total amount of emissions generated in the production of y_1^s. 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 the consumption (across columns) of all downstream countries/sectors (including itself). 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

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

traces backward industrial linkages across upstream countries/industries (as different stages of production) from a global supply chain perspective.

Therefore, the producer's perspective (summing elements in a row) decomposes each country's total emissions by industry according to where the consumption is made, while the supply chain perspective (summing elements in a column) 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 global supply chain 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 export by the home country. Such a backward industrial-linkage-based perspective aligns well with case studies of global supply chains of specific products 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 (country/emission source) source 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 final goods and services production 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 an MRIO table becomes

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

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

$$\begin{aligned}(I - A^{ss})^{-1}E^{s*} &= (I - A^{ss})^{-1}\left(\sum_{r\neq s}^{G} Y^{sr} + \sum_{r\neq s}^{G} A^{sr}X^r\right) \\ &= \sum_{r\neq s}^{G} B^{ss}Y^{sr} + \sum_{r\neq s}^{G} B^{sr}Y^{rr} + \sum_{r\neq s}^{G} B^{sr}\sum_{t\neq s,r}^{G} Y^{rt} + \sum_{r\neq s}^{G} B^{sr}Y^{rs} + \sum_{r\neq s}^{G} B^{sr}A^{rs}(I - A^{ss})^{-1}Y^{ss}\end{aligned} \quad (10)[5]$$

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.

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

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.

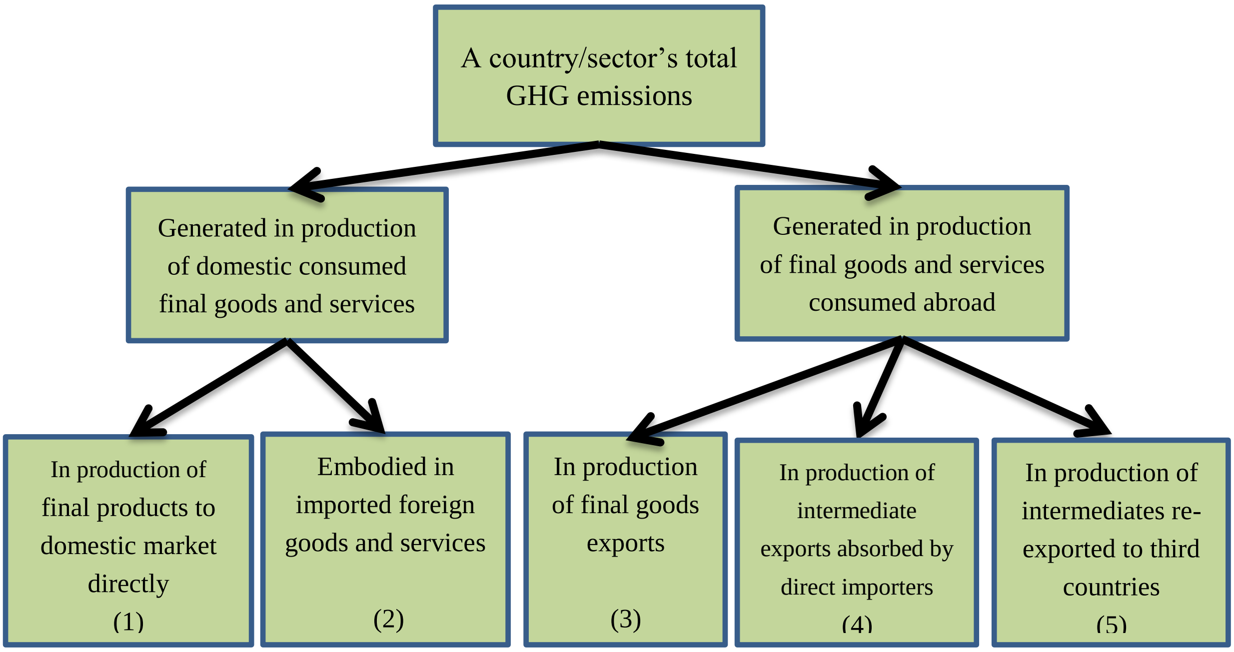
- The first term: domestically produced and consumed final goods and services (Y^{ss}).
- The second term: domestically produced intermediate goods exports ($A^{sr}\sum_{t}^{G} B^{rt}Y^{ts}$) which are used by other countries to produce either intermediate or final goods and services shipped back to the source country as imports and consumed there. [6]
- The third term: domestically produced final goods and service exports that are consumed by all of its trading partners (Y^{sr}).

[5]A detailed mathematical proof of equation (10) is provided in Appendix A.1.
[6]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.

- The fourth term: domestically produced intermediate goods and services exported to country r for the production of final products consumed in country r (Y^{rr})
- The fifth term: domestically produced intermediate goods exports to other countries producing their final goods and service exports to third countries Y^{rt}).

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 at 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 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[7]. 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.

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

$$\hat{F}_c B\hat{Y} = \begin{bmatrix} \hat{F}_c^1 & 0 & \cdots & 0 \\ 0 & \hat{F}_c^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{F}_c^G \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} \hat{Y}^1 & 0 & \cdots & 0 \\ 0 & \hat{Y}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{Y}^G \end{bmatrix}$$
$$= \begin{bmatrix} \hat{F}_c^1 B^{11}\hat{Y}^1 & \hat{F}_c^1 B^{12}\hat{Y}^2 & \cdots & \hat{F}_c^1 B^{1G}\hat{Y}^G \\ \hat{F}_c^2 B^{21}\hat{Y}^1 & \hat{F}_c^2 B^{22}\hat{Y}^2 & \cdots & \hat{F}_c^2 B^{2G}\hat{Y}^G \\ \vdots & \vdots & \ddots & \vdots \\ \hat{F}_c^G B^{G1}\hat{Y}^1 & \hat{F}_c^G B^{G2}\hat{Y}^2 & \cdots & \hat{F}_c^G B^{GG}\hat{Y}^G \end{bmatrix} \quad (13)$$

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, which is the total requirement matrix that describes the amount of gross output in producing country s required for a one-unit increase in the final demand in destination country r. 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 emission source. Five types of emission source 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 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

[7] 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 $G*N$, 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.

supply chain of a particular final good or service y_j^s.

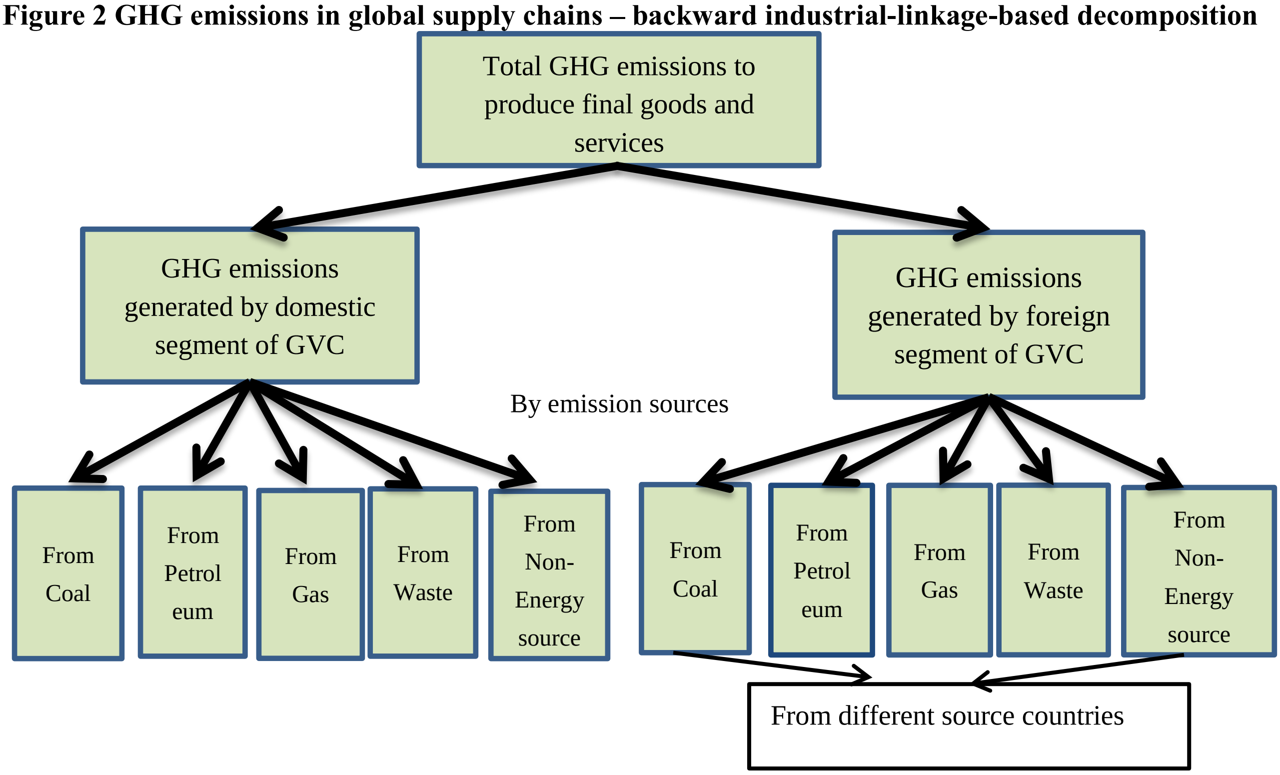
Based on equation (13), we can decompose the total emissions of a final good or service by production stages and emission sources in a global supply chain based on backward industrial linkage as follows.

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

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

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 the source countries. Note that $\sum_{c=1}^{5} F_c^s = F^s$, that is, emission intensities by emission sources 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 good or service in a global supply chain based on backward industrial linkage made by equations (14) is shown in Figure 2.

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



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:

$$P_c^{consumer}(y_i^r) = \sum_s^G \frac{y_i^{sr}}{y_i^r} P_c(y_i^s) \; for\ c=1,2,3,4,5 \quad ; i=1,2,...N \tag{16}$$

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 consumption as an example, the production plus net transfer method 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 of whether backward or forward linkage computation is used.

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 embodied emissions in trade in the literature have not made a clear distinction between emissions as 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 embodied emissions in trade and two measures of emissions embodied in a country's gross exports at a disaggregated (bilateral /sector) level

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 *r*, are the emissions generated in sector *i* to produce, directly and indirectly, gross products exported from *r* to any other destination country except the country *r* itself (e.g., exports from the US chemical sector would include gross exports from US steel and machinery sectors in addition to 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.

The term emissions embodied in a country's gross exports, which we labeled EEG, refers to emissions 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

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

This 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 four 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 finally absorbed in the direct importing country *r*, and are either
3. returned (re-imported) to the exporting country *s*, or
4. 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 with 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. 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[8]. To facilitate the understanding of the three terms in the emissions trade measure defined in equation (23), we provide the following intuitive interpretations.

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 and 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

[8]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.

the 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. Neither emissions export measure captures 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.

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

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 domestic sectors that contribute to the production of a particular sector's gross exports.

We define emissions associated with 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:

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

It is easy to see 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.

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

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

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

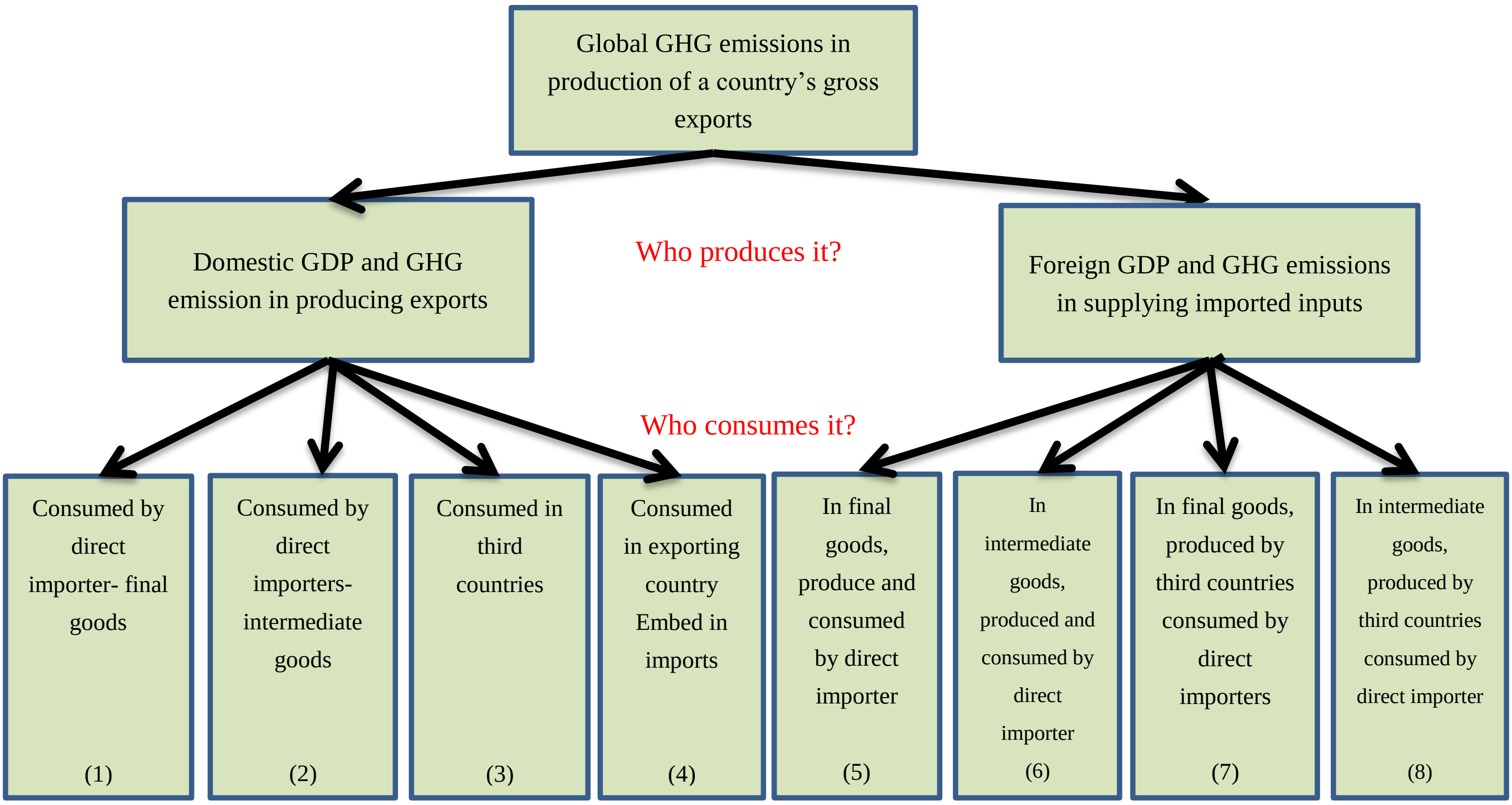
Each term in equation (28) has an intuitive interpretation. The first term, $(F^r B^{rs})^T \# Y^{sr}$, is the importer's (country r) emissions embodied in the final exports of country s to country r. The second term, $(F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr})$, is the importer's emissions embodied in 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

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

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).

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



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.

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 at only 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 embodied emissions in trade (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 emissions 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 these measures of embodied emissions in trade 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	Definition equation #
EEX_F	Embodied emissions exports, forward-linkage-based	1.Emissions generated in production 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	**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 side 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 [9] to demonstrate how this framework can help to gain a better 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

Following Figures 1, 2, and 3, we first show how the accounting framework works at the national level.

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 domestic 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 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 of GDP in China is higher than that in the US (Davis and Caldiera 2010) (also see Appendix B4).

Part of the CO_2 emissions induced by domestic final demand may occur due to international trade through production sharing between home and foreign countries, as shown 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 is 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 goods in their early stage of

[9] www.wiod.org

development. Appendix B1 provides more detailed forward industrial-linkage-based decomposition results at the national level for the years 1995 to 2009.

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

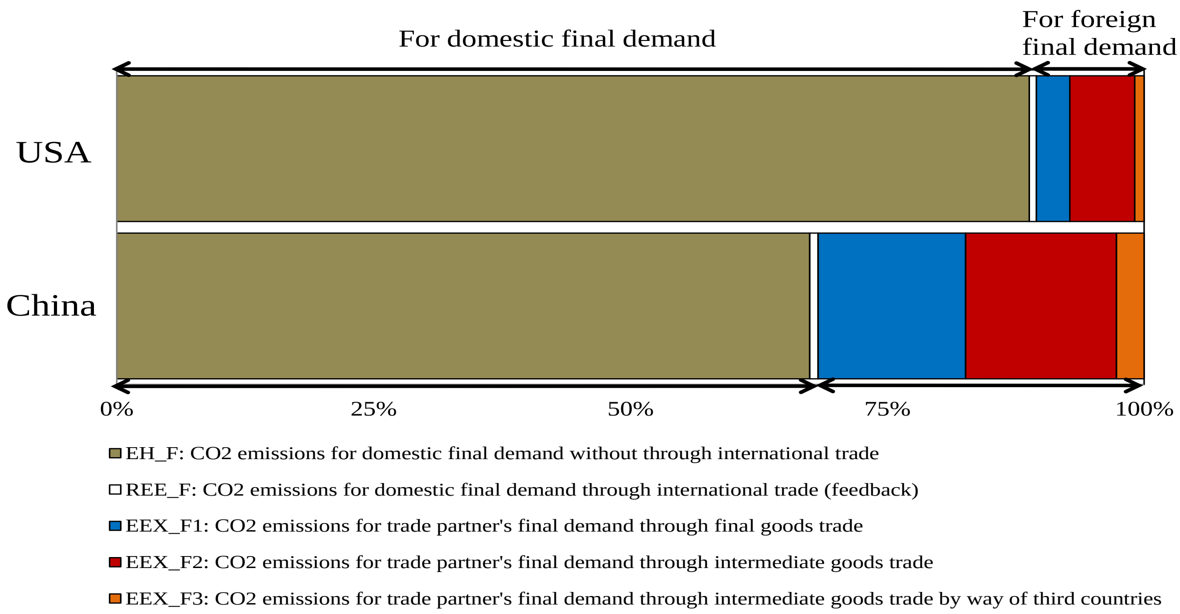


Figure 5 uses Germany and China as an example to show how CO_2 emissions are generated in GVCs by different emission sources when these two countries produce final goods and services. This figure follows the backward industrial-linkage-based upstream decomposition method (Figure 2). The foreign emissions 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 on the countries' CO_2 emission intensities, their cross country production sharing arrangements and the way they participate in GVCs. China's CO_2 emission intensity is normally 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. Appendix B2 provides more detailed backward industrial-linkage-based decomposition results at the national level for the years between 1995 and 2009.

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)

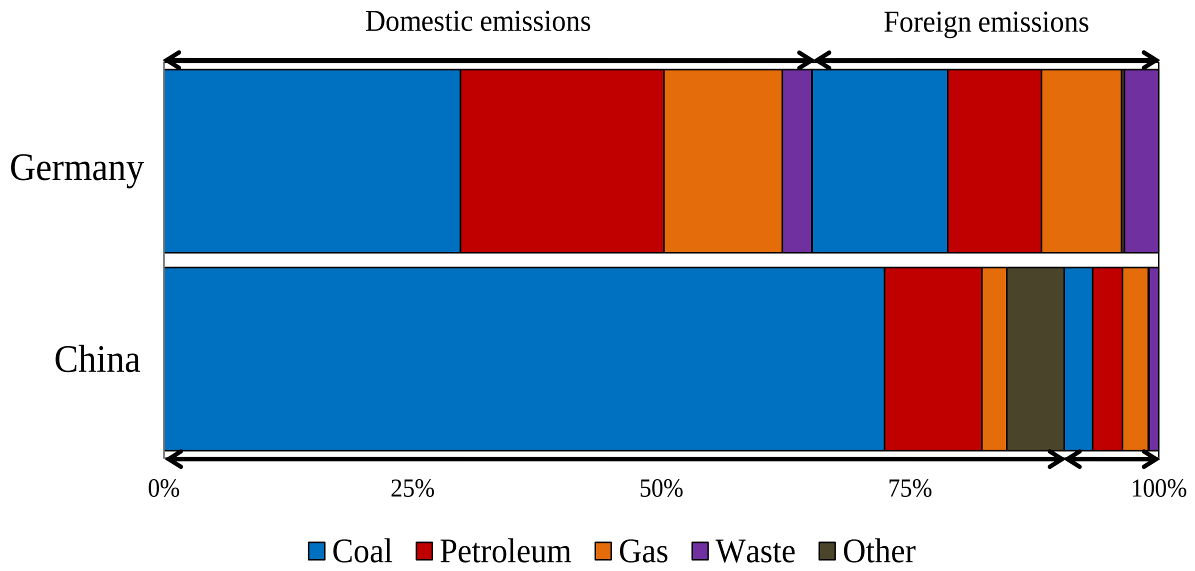


Figure 6 Emissions embodied in gross exports (backward industrial-linkage-based decomposition, 2009)

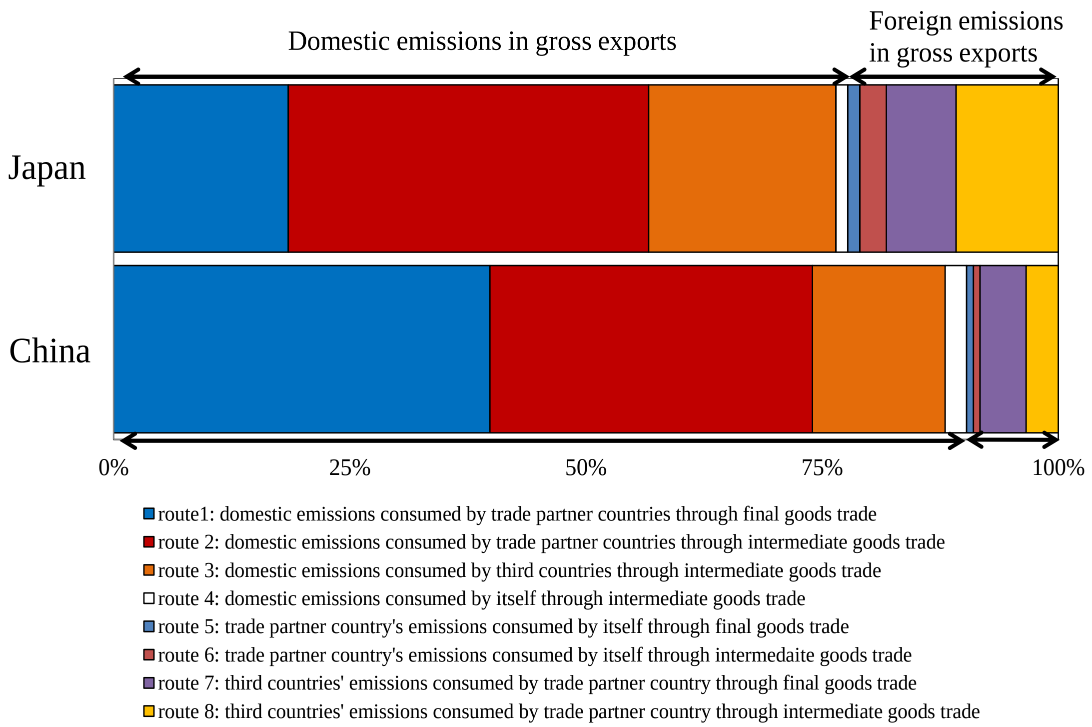


Figure 6 shows how Japan and China's gross exports generate both domestic and foreign CO_2 emissions by different GVC routes in 2009 (cf. Davis and Caldiera 2010). This figure corresponds to the backward industrial-linkage-based decomposition on gross exports (Figure 3). Compared to Japan, domestic produced CO_2 emissions in China's gross exports 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. China joins GVCs mainly by providing final products, as a result of its comparative advantage in assembly, 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.

The share of foreign CO_2 emissions in gross exports also depends on both the way a country participates in GVCs and 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 type of 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 intermediate goods and services to produce a third country's exports (route 7 and 8). Given the extension of international fragmentation of production, this part of emissions in international trade tends to increase quickly if no global treaty is in place. We report more detailed backward industrial-linkage-based decomposition results on CO_2 emissions in gross exports at the national level for the years between 1995 and 2009 in Appendix B3.

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

As discussed in section 2, the accounting framework proposed in this paper can 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 metal products GVCs and are directly and indirectly important trade partners of the US, while being located in different regions: North America, Asia, and Europe. In addition, for most countries, the metal industry is always one of the largest emitters, with a relatively high carbon intensity.

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)

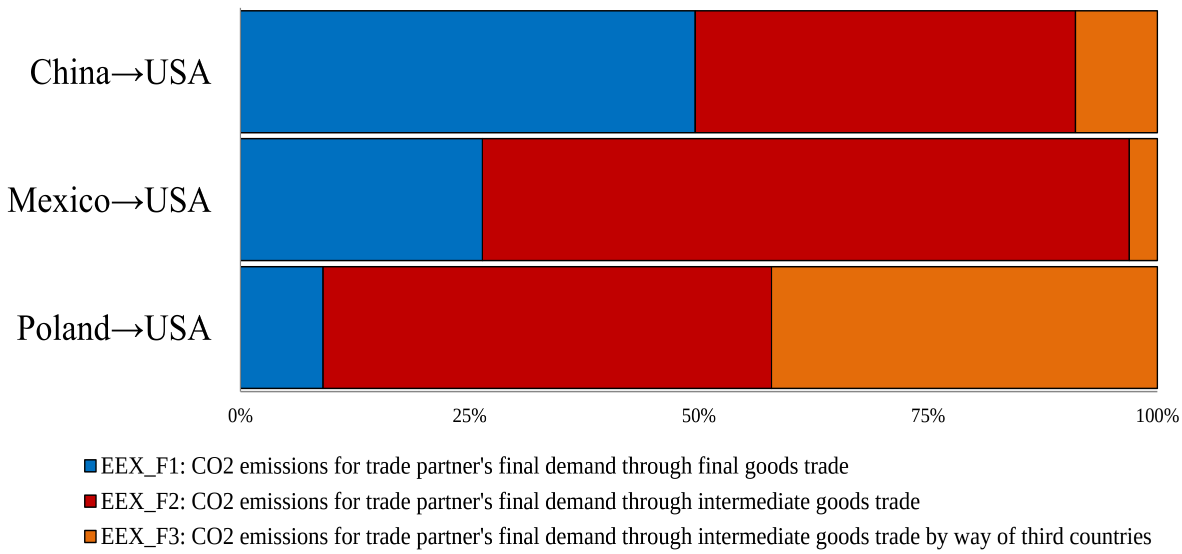


Figure 7 shows the CO_2 emissions in the metal industries in these three countries from activities to satisfy US's final demand via different GVC routes. The pattern is mainly determined by a country's position and participation in GVCs. China exports large quantities of final products to the US, so 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 since Mexico 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 consumer and is embedded in the EU economy, so it is located far upstream in the metal products GVCs.

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 can definitely help us to understand how a country's position and participation in a GVC impact on the sources of its CO_2 emissions at industry level.

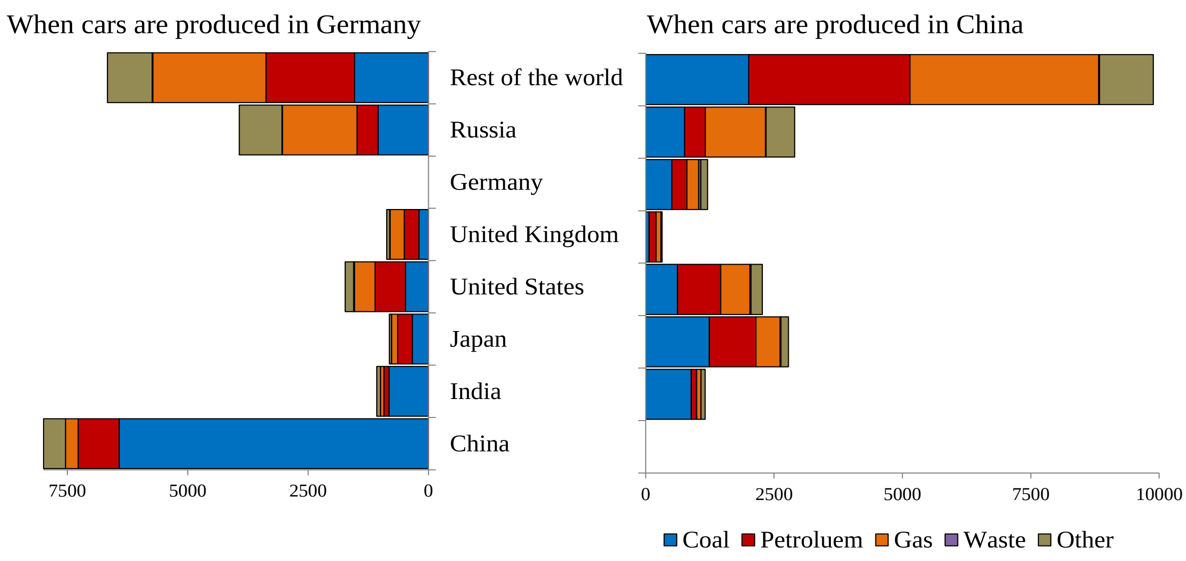
Following the accounting method represented in Figure 2, we use German-made and Chinese-made cars as an example to demonstrate how these two large car producers cause upstream CO_2 emissions in automobile GVCs. Figure 8 shows China, the rest of the world (RoW), and Russia are the countries most affected by car production in Germany, besides Germany itself. On the one hand, this is because these three countries are located upstream of Germany's car value chain through providing intermediate goods and services directly and 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 China's car makers 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[10]. 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.

Following the accounting framework proposed in Figure 3, Figure 9 demonstrates how a country's gross exports generate both domestic and foreign CO_2 emissions through different GVC routes at the bilateral level for a specific product. Germany, Mexico and China's electrical product exports to the US are used as an example here. These three countries were the largest trade 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

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

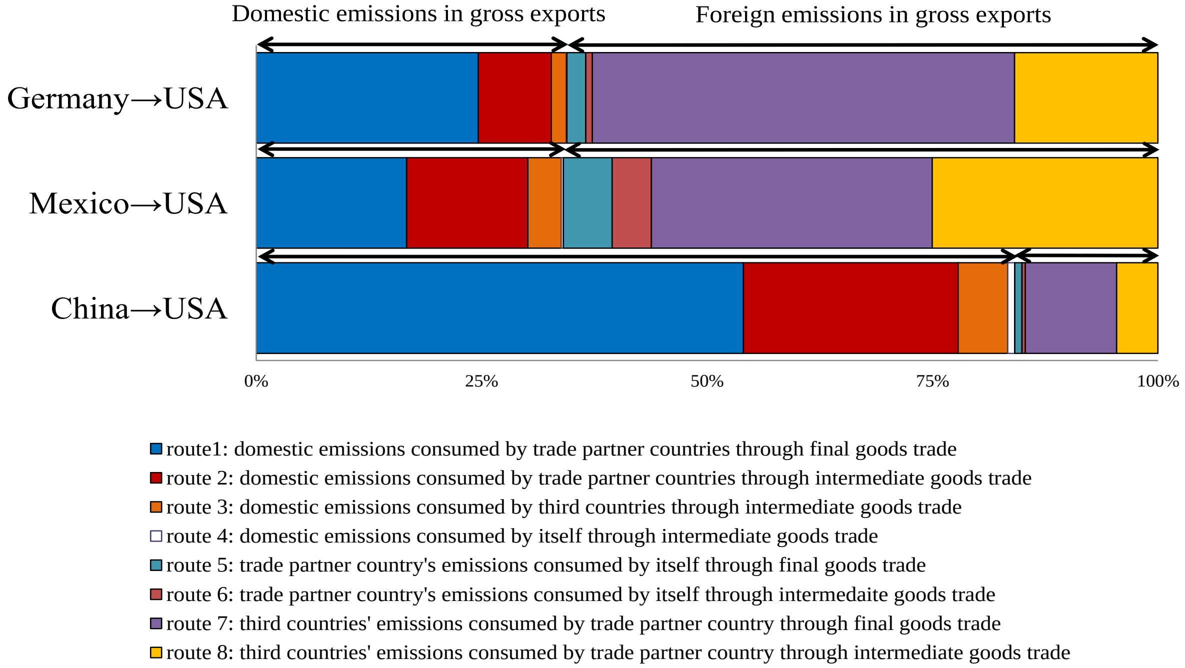
emissions. This difference is caused by several reasons that may operate in opposing directions: a higher domestic carbon intensity in producing goods and services leads to a larger portion of domestic emissions; a higher proportion of foreign intermediate imports in a country's exports (implying a higher participation in GVCs), leads to a smaller portion of domestic emissions.

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



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 and 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 account 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 and 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

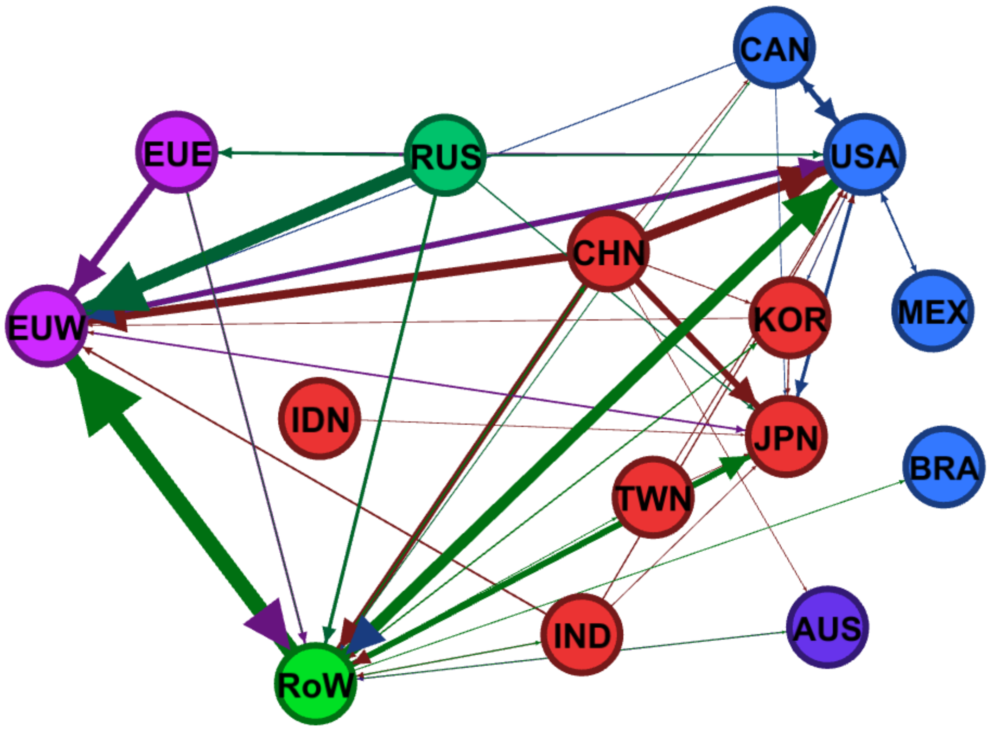
As illustrated in Table 1b, at the bilateral-aggregate and country-aggregate level, there is no difference between the forward and backward industrial-linkage-based embodied emissions exports measures. Here, for simplicity, we define country A's total CO_2 emissions induced by its partner country B's final demand as CO_2 emissions export from country A to B (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 bilateral relationship 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, especially from the RoW, the US and the EUW. This is mainly because China has been deeply integrated into GVCs not just as the largest final goods exporter, but also as an important intermediate goods importer which causes the CO_2 emissions in the upstream countries which provide these intermediate products to China directly and indirectly. The most important concern is the increasing bilateral CO_2 emissions trade between China and the RoW which are both developing economies with relatively lower environmental regulation (they both are Annex B countries in Kyoto Protocol).

3.4 The potential environmental cost of GVCs

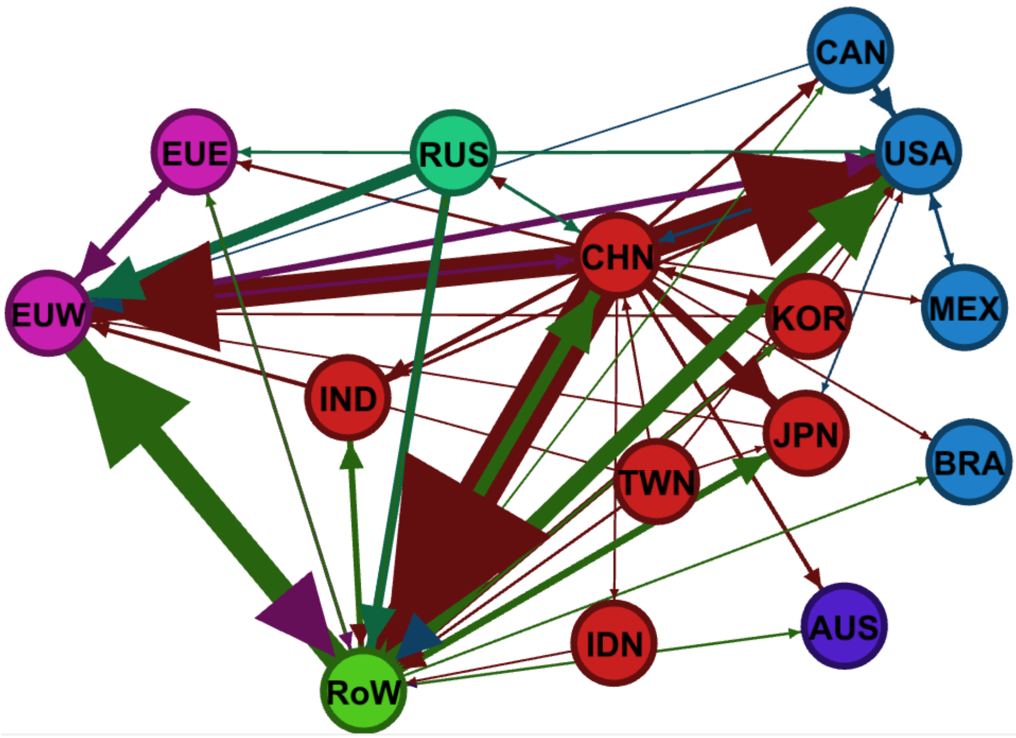
As discussed in section 2, the proposed accounting framework allows us to trace both value-added and embodied emissions concurrently in a consistent manner. By dividing the "trade in value-added" by "trade in CO_2 emissions" (EEX_F^{sr}), the potential environmental cost can be obtained. The results for all WIOD countries for both 1995 and 2009 are shown in Figure 11. The environmental cost of value-added exports for Eastern Europe, China, India and the RoW is higher than that for other developed countries for both years. The cost decreases for almost all countries during this 15-year period. At the country to country level, more variation in the changing patterns can be observed. For example, one of the high-carbon interactions is Estonia's export of value added to Romania in 1995. This situation changed dramatically, as the high-carbon trade moves to the flow from Estonia to Mexico, the Netherlands, and Turkey in 2009. In addition, the potential environmental cost of the bilateral emissions trade can also be identified by different emission sources, as shown in Figure B2 (Appendix B). To get one unit of value added from international trade, China, Indonesia, and some eastern Europe countries, like Bulgaria, Russia and Estonia, generate relatively more coal-based CO_2 emissions. Malta, Greece, Cyprus and Taiwan emit more petroleum-based CO_2 emissions. Russia, Romania, Canada and Mexico produce more natural gas-based CO_2 emissions. These figures can provide a better understanding of how different countries produce value added and CO_2 emissions as well as their ratios.

Figure 10 Bilateral trade in CO_2 emissions

1995

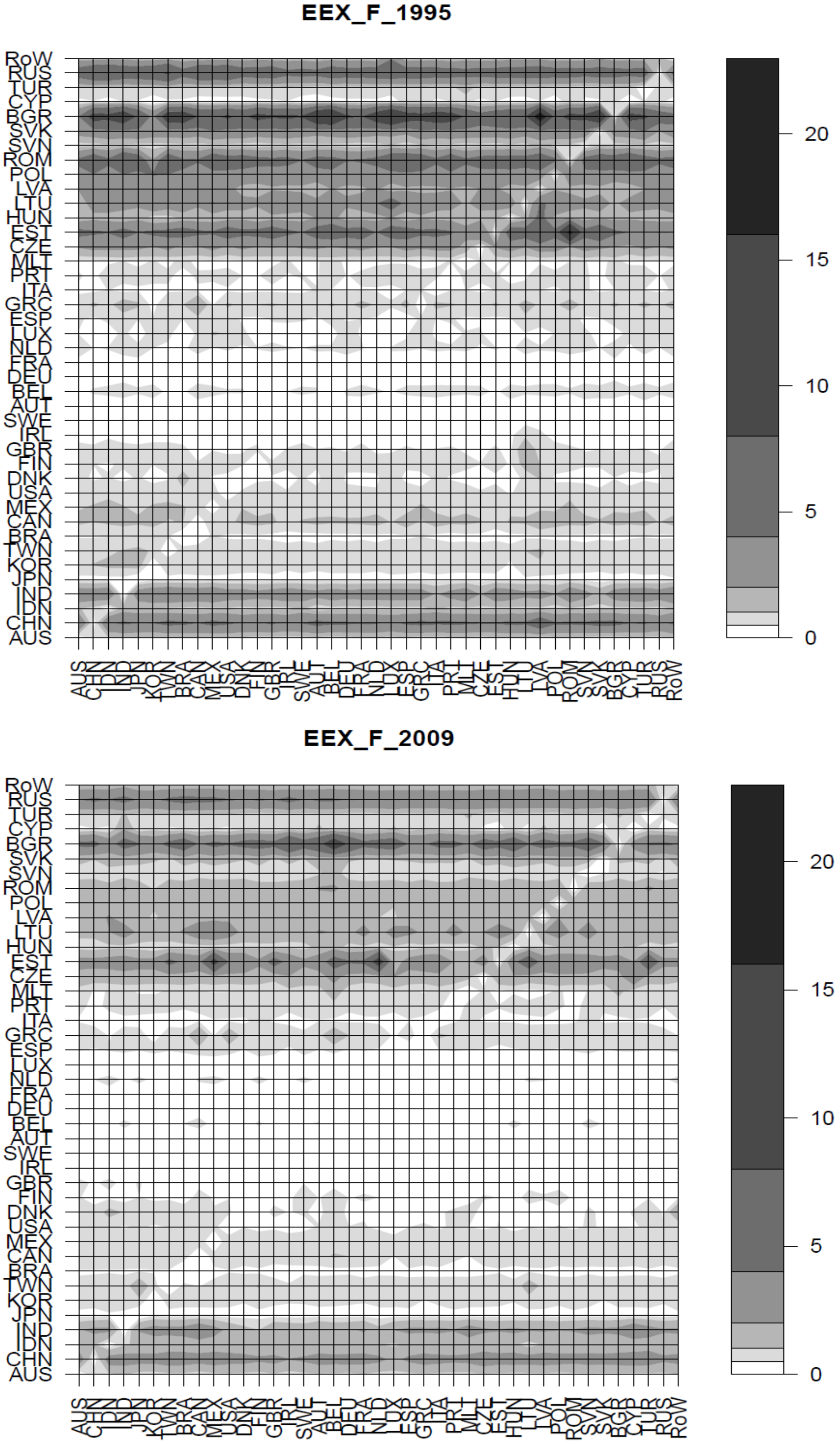


2009



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.

Figure 11 Potential environmental cost of trade (trade in CO_2 emissions / trade in value added, kt/million US$, base year: 1995)



3.5 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 partly depend on a country's position and participation in GVCs. Figure 12 shows the relationship between a country's GVC participation (the level of foreign value-added in gross exports) and the share of domestic 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 rings with different colors surrounding the bubbles show two different GVC routes (through final goods trade or intermediate goods trade) and two kinds of products (energy goods and non-energy goods).

The main features of Figure 12 can be summarized as follows.

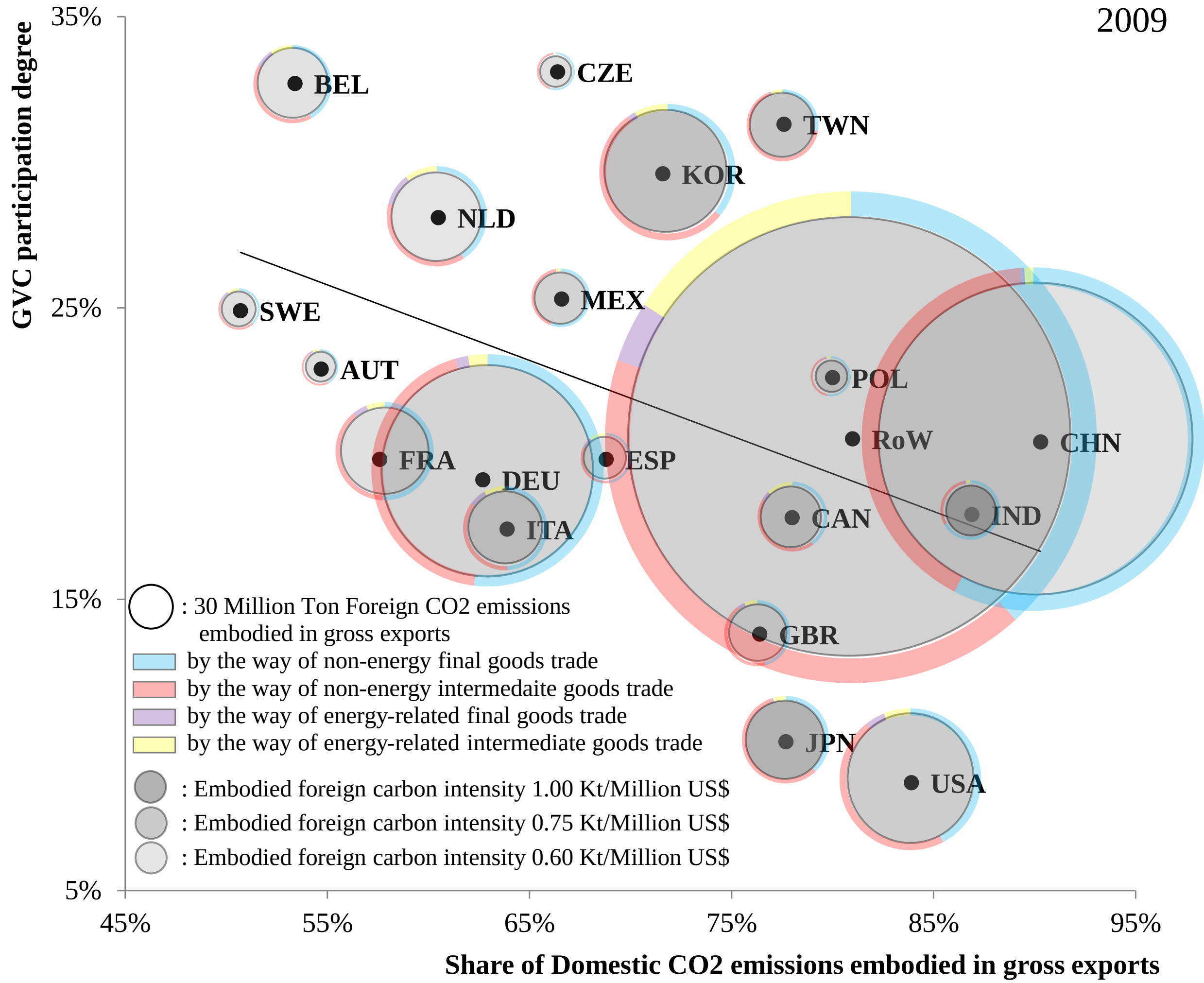
1. The higher the imported content in a country's exports, the smaller the domestic CO_2 emissions in its gross exports. When a country uses more foreign intermediate inputs to substitute for domestic inputs in producing exports, relatively less CO_2 emissions will be generated domestically.
2. The relatively 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.
3. 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.
4. Developing economies join GVCs mainly by providing relatively more final goods, which is clearly different from developed economies and is 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 the RoW they are mainly as a result of final goods trade.
5. The RoW and China 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.
6. 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.

3.6 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 (taken 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. We expand on Peters et al. (2011) (corresponding to Figure 1, the forward industrial-linkage-based decomposition method) to show the consumption-based and production-based emissions and their evolution from 1995 to 2009 for both Annex B and Non-Annex B country groups. In addition, we investigate how the international transfer of emissions occurs through various GVC routes with different carbon intensities.

Figure 13 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 increasing pattern for Annex B countries' emissions in 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. 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.

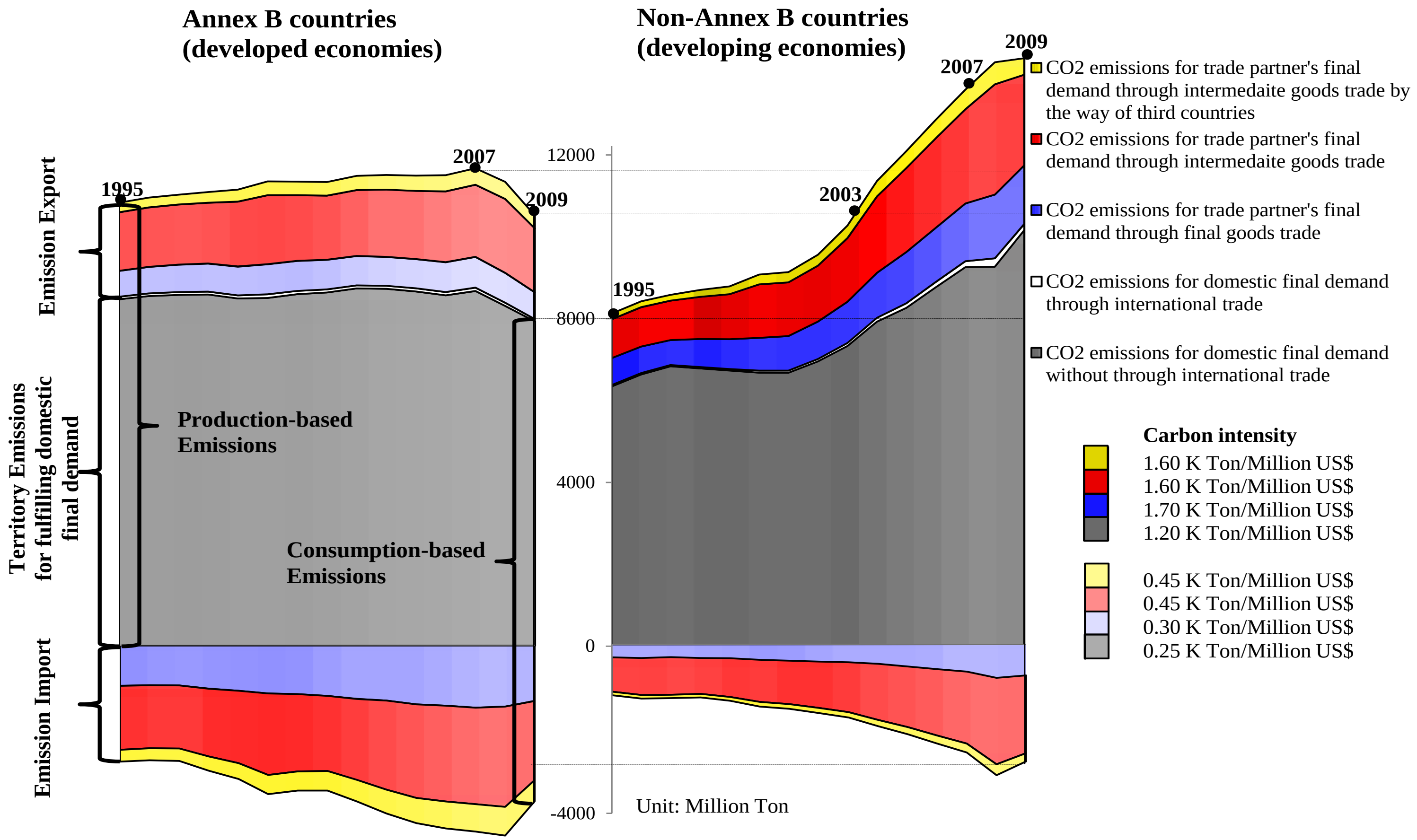
Figure 12 The relationship between GVC participation degree and CO_2 emissions (2009)



With the information about carbon intensity along different GVC routes, the major points observed from Figure 13 can be summarized as follows.

1. Goods and services produced to satisfy domestic final demand generally have a lower emission intensity than that from satisfying foreign final demand for both Annex B and Non-Annex B countries. In other words, the international trade in carbon-intensive products tends to have increased in the last 15 years.
2. An improvement of carbon intensity for both Annex B and Non-Annex B counties can be observed. However, the carbon intensity for Non-Annex B countries in 2009 is still higher than that for Annex B countries' 1995 level. As a result, Annex B countries have more low-carbon exports, but more high-carbon imports; Non-Annex B countries have more high-carbon exports, but more low-carbon imports.
3. The rapid economic growth of Non-Annex B countries with relatively high carbon intensity during the period, especially China, boosts both domestic emissions and emissions trade. At the same time, the increasing GVC participation accompanying more trade in intermediate goods clearly spurs on emissions embodied in trade.
4. 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.

Figure 13 Consumption-based vs. production-based CO_2 emissions and emissions transfer through different GVC routes (1995-2009)



3.7 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. Table 2 extends Table 1b to real data to show the bilateral relationship between different measures of embodied emissions in trade for Electrical and Optical Equipment (WIOD sector 14) trade between China and Japan in 2009. To provide a better understanding of the differences between these measures, we apply both forward and backward industrial-linkage-based decomposition results to measure China's Released Comparative Advantage (RCA[11]).

The traditional RCA indicator (Balasa 1966) is based on gross exports. As shown by Koopman et al. (2014), this type of RCA may be misleading when gross exports embody large foreign value added. The better way is to use value-added exports to measure RCA which can avoid the so-called "double counting" problem in gross 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. For simplicity, we call the RCA based on forward industrial linkage the "downstream-driven RCA" indicator. 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. For simplicity, we call the RCA based on backward industrial linkage the "upstream-driven RCA" indicator.

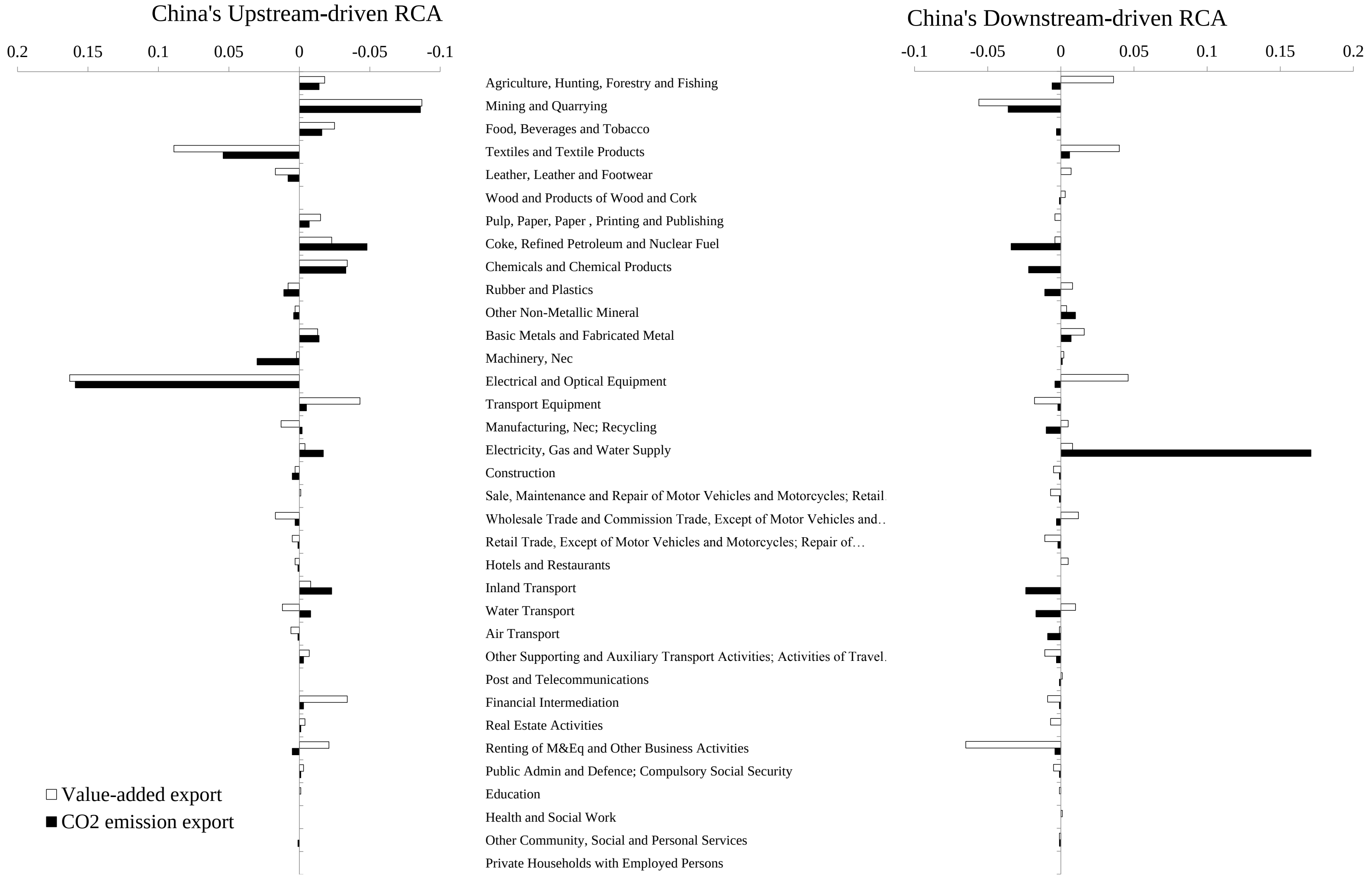
The upper part of Figure 14 shows China's sectoral downstream-driven RCA ranking for both value-added and CO_2 emissions exports. For value-added exports, Electrical and Optical Equipment (WIOD sector 14), Textiles and Textile Products (WIOD sector 4) and Agriculture, Hunting, Forestry and Fishing (WIOD sector 1) show the highest RCA since all these sectors generate more value-added for fulfilling a 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 China's energy sector emits large amounts of CO_2 emissions for foreign final demands which are not seen in traditional trade statistics since there is a negligible amount of Chinese electricity exported.

[11] 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.

Table 2 The relationships among different measures of embodied CO_2 emissions and their applications

Level	Indicators / Example	EEX	EEX_F	EEX_B	REE_F	REE_B	EEG_F	EEG_B	EEX_F+REE_F	EEX_B+REE_B
Bilateral-sector	(China→Japan, WIOD14)	38,634	867	39,206	31	1,395	880	39,427	898	40,601
Bilateral Aggregate	(China→Japan)	147,839	147,022	147,022	4,645	4,645	152,256	152,256	151,667	151,667
Country-Sector	(China→World, WIOD14)	557,698	12,463	557,698	428	19,804	12,891	574,614	12,891	577,502
Country Aggregate	（China→World）	1,971,179	1,971,179	1,971,179	50,471	50,471	2,021,650	2,021,650	2,021,650	2,021,650

Figure 14 Downstream-driven vs. upstream-driven RCA for both value-added exports and CO_2 emissions exports (2009)



The bottom part of Figure 14 shows the upstream-driven 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, 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 upstream sectors. Both downstream-driven and upstream-driven RCA indicators have their own roles in helping us better understand a country's RCA from different perspectives.

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 combines recent GVC-based measures with existing emissions trade related measures into one unified accounting framework, in which both value added and emissions can be systematically traced at country, bilateral, and sector levels through various GVC routes. It consistently defines various trade related embodied emissions measures at country, bilateral and sector levels and clearly quantifies their relations. Such a framework is not only able to identify value-added and emissions generated from each production stage (slice value chains), but can also identify the special trade routes by which value added and emissions are created. By combining value-added and emissions accounting in a consistent way, the potential environmental cost along GVCs can also be estimated (e.g., amount of emissions per unit of value added) from different perspectives (production, consumption and trade). This provides measures that clearly distinguish emissions of self-responsibility (emissions from satisfying domestic final demands without international trade) and shared responsibility (emissions through international trade) between producers and consumers located in different territories as well as their relative economic benefit to environmental cost ratio.

To show how this proposed accounting framework works, selected empirical examples based on data from the WIOD were presented. These results show:

1) Since most countries have been deeply involved in GVCs in the past two decades, a growing share of their emissions are produced to satisfy foreign countries' final demands. However, due to the difference in GVC participation patterns and carbon intensity, developing countries' emissions exports take a relatively large share of their total production-based emissions and these are more likely to be created through trade in final goods than for developed countries.
2) The differences in carbon intensity and position in GVCs between developed and developing economies also cause "carbon leakage" through international trade: developed economies tend to import more high-carbon-intensity intermediate goods from developing economies in producing final goods and services. The environmental cost for generating one unit of GDP in domestic production is lower than that incurred through international trade. The main driver is the high-carbon-intensity trade in intermediates, which has grown rapidly during the period covered by WIOD.
3) "Carbon leakage" also happens inside non-Annex B countries, for example, between the largest two developing economies, which are China and countries in the RoW. The magnitude of their bilateral CO_2 emissions trade has exceeded all bilateral trade between any developed economy blocks and China (the EU-China or the US-China). This could be a great concern since both China and countries in the RoW are Non-Annex B economies and both have relatively weak environmental regulations.
4) The environmental cost measured by "trade in CO_2 emissions" divided by "trade in value added" shows a decreasing tendency for both Annex B and Non-Annex B countries from 1995 to 2009. Although the pace of decrease for Non-Annex B countries is faster than that for Annex B countries, the rapid economic growth of Non-Annex B countries has generated larger emissions in absolute terms: that is, the decrease of environmental cost in per unit GDP could not cancel out the impact coming from the increasing scale of economic activity in Non-Annex B countries.

Appendix A [12]

A.1 Step by step proof of Equation (10) in the main text

Write $L^{ss} = (I - A^{ss})^{-1}$, then the last term of equation (9) in the main text can be written as

$$L^{ss}E^{s*} = L^{ss}(\sum_{r\neq s}^{G} Y^{sr} + \sum_{r\neq s}^{G} A^{sr}X^{r}) \tag{A1}$$

Using the gross output X^r decomposition equation

$$X^{r} = \sum_{t}^{G} B^{rt}\sum_{u}^{G} Y^{tu} \ ,$$

E^{s*} can be expressed as

$$\begin{aligned} E^{s*} &= \sum_{r\neq s}^{G} Y^{sr} + \sum_{r\neq s}^{G} A^{sr}\sum_{t}^{G} B^{rt}\sum_{u}^{G} Y^{tu} \\ &= \sum_{r\neq s}^{G} Y^{sr} + \sum_{r\neq s}^{G} A^{sr}B^{rs}\sum_{t\neq s}^{G} Y^{st} + \sum_{r\neq s}^{G} A^{sr}\sum_{t\neq s}^{G} B^{rt}Y^{tt} + \sum_{r\neq s}^{G} A^{sr}\sum_{t\neq s}^{G} B^{rt}\sum_{u\neq s,t}^{G} Y^{tu} \\ &+ \sum_{r\neq s}^{G} A^{sr}\sum_{t\neq s}^{G} B^{rt}Y^{ts} + \sum_{r\neq s}^{G} A^{sr}B^{rs}Y^{ss} \end{aligned} \tag{A2}$$

Rearranging gives

$$\begin{aligned} E^{s*} &= \sum_{r\neq s}^{G} Y^{sr} + \sum_{t\neq s}^{G} A^{st}B^{ts}\sum_{r\neq s}^{G} Y^{sr} + \sum_{t\neq s}^{G} A^{st}\sum_{r\neq s}^{G} B^{tr}Y^{rr} + \sum_{t\neq s}^{G} A^{st}\sum_{u\neq s,r}^{G} B^{tu}\sum_{r\neq s}^{G} Y^{ur} \\ &+ \sum_{t\neq s}^{G} A^{st}\sum_{r\neq s}^{G} B^{tr}Y^{rs} + \sum_{t\neq s}^{G} A^{st}B^{ts}Y^{ss} \end{aligned} \tag{A3}$$

Inserting equation (A3) into (A1) gives

$$\begin{aligned} L^{ss}E^{s*} &= \left(L^{ss} + L^{ss}\sum_{t\neq s}^{G} A^{st}B^{ts} \right)\sum_{r\neq s}^{G} Y^{sr} + L^{ss}\sum_{t\neq s}^{G} A^{st}\sum_{r\neq s}^{G} B^{tr}Y^{rr} + L^{ss}\sum_{u\neq s}^{G} A^{su}\sum_{t\neq s,r}^{G} B^{ut}\sum_{r\neq s}^{G} Y^{tr} \\ &+ L^{ss}\sum_{t\neq s}^{G} A^{st}\sum_{r\neq s}^{G} B^{tr}Y^{rs} + L^{ss}\sum_{t\neq s}^{G} A^{st}B^{ts}Y^{ss} \end{aligned} \tag{A4}$$

Using the properties of inverse matrices, we can obtain the identity

[12] We acknowledge Dr. KunFu Zhu's help on related mathematical derivations.

$$\begin{bmatrix} I-A^{11} & -A^{12} & \cdots & -A^{1G} \\ -A^{21} & I-A^{22} & \cdots & -A^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{G1} & -A^{G2} & \cdots & I-A^{GG} \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} = \begin{bmatrix} I & 0 & \cdots & 0 \\ 0 & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & I \end{bmatrix}$$

$$= \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} I-A^{11} & -A^{12} & \cdots & -A^{1G} \\ -A^{21} & I-A^{22} & \cdots & -A^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{G1} & -A^{G2} & \cdots & I-A^{GG} \end{bmatrix} \tag{A5}$$

From (A5) we obtain

$$(I-A^{ss})B^{sr} - \sum_{t \neq s}^{G} A^{st} B^{tr} = 0 \tag{A6}$$

$$(I-A^{ss})B^{ss} - \sum_{r \neq s}^{G} A^{sr} B^{rs} = I = B^{ss}(I-A^{ss}) - \sum_{r \neq s}^{G} B^{sr} A^{rs} \tag{A7}$$

From equations (A6) and (A7), we can obtain flow relationships between global block inverse matrices and local inverse matrices:

$$B^{ss} = L^{ss} + L^{ss} \sum_{t \neq s}^{G} A^{st} B^{ts}, \quad B^{sr} = L^{ss} \sum_{t \neq s}^{G} A^{st} B^{tr},$$

$$B^{st} = L^{ss} \sum_{r \neq s}^{G} A^{sr} B^{rt}, \quad L^{ss} \sum_{t \neq s}^{G} A^{st} B^{ts} = \sum_{r \neq s}^{G} B^{sr} A^{rs} L^{ss}$$

Inserting these four equations into (A4) gives

$$L^{ss} E^{s*} = B^{ss} \sum_{r \neq s}^{G} Y^{sr} + \sum_{r \neq s}^{G} B^{sr} Y^{rr} + \sum_{r \neq s}^{G} B^{sr} \sum_{t \neq s,r}^{G} Y^{rt} + \sum_{r \neq s}^{G} B^{sr} Y^{rs} + \sum_{r \neq s}^{G} B^{sr} A^{rs} L^{ss} Y^{ss} \tag{A8}$$

which is exactly the same as equation (10) in the main text. We can further show that

$$\sum_{r \neq s}^{G} B^{sr} Y^{rs} + \sum_{r \neq s}^{G} B^{sr} A^{rs} L^{ss} Y^{ss} = \sum_{t \neq s}^{G} A^{st} \sum_{r \neq s}^{G} B^{tr} Y^{rs} + \sum_{t \neq s}^{G} A^{st} B^{ts} Y^{ss} = \sum_{t \neq s}^{G} A^{st} \sum_{r}^{G} B^{tr} Y^{rs} \tag{A9}$$

A.2 Step by step proofs of Equations (18), (19) and (20) in the main text

As equation (1) in the main text shows, the gross exports of country s to country r can be decomposed into two parts: final goods exports and intermediate goods exports,

$$E^{sr} = Y^{sr} + A^{sr} X^{r} \tag{A10}$$

As illustrated in section 2.1 in the main text, final goods exports can be easily decomposed into domestic and foreign value added by directly applying Leontief's insight. However, the decomposition of intermediate goods exports is more complex. It cannot be achieved by simply multiplying the Leontief inverse with gross intermediate exports because the latter has to be solved from the MRIO models first for any given level of final demand. Wang et al. (2013) provide a method to overcome this endogeneity issue by expressing all intermediate trade flows as different countries' final demands according to where the goods or services are absorbed. Following their method, the gross output of country r can be decomposed into the following components according to where it is finally absorbed (obtained from equation (12) in the main text by pick-up country r only):

$$\begin{aligned} X^{r} &= \sum_{t}^{G} B^{rt} \sum_{u}^{G} Y^{tu} = B^{rr} \sum_{t}^{G} Y^{rt} + \sum_{t \neq s,r}^{G} B^{rt} \sum_{u \neq s,t}^{G} Y^{tu} + B^{rs} \sum_{t \neq s}^{G} Y^{st} \\ &= \sum_{r \neq s}^{G} B^{rr} Y^{rr} + \sum_{r \neq s}^{G} \sum_{t \neq s,r}^{G} B^{rt} Y^{tt} + \sum_{r \neq s}^{G} B^{rr} \sum_{t \neq s}^{G} Y^{rt} + \sum_{r \neq s}^{G} \sum_{t \neq s,r}^{G} B^{rt} Y^{tr} \\ &+ \sum_{r \neq s}^{G} \sum_{t \neq s,r}^{G} B^{rt} \sum_{u \neq s,r,t}^{G} Y^{tu} + \sum_{r \neq s}^{G} \sum_{t \neq s}^{G} B^{rt} Y^{ts} + \sum_{r \neq s}^{G} B^{rs} Y^{ss} + \sum_{r \neq s}^{G} B^{rs} Y^{sr} + \sum_{r \neq s}^{G} B^{rs} \sum_{t \neq s,r}^{G} Y^{st} \end{aligned} \tag{A11}$$

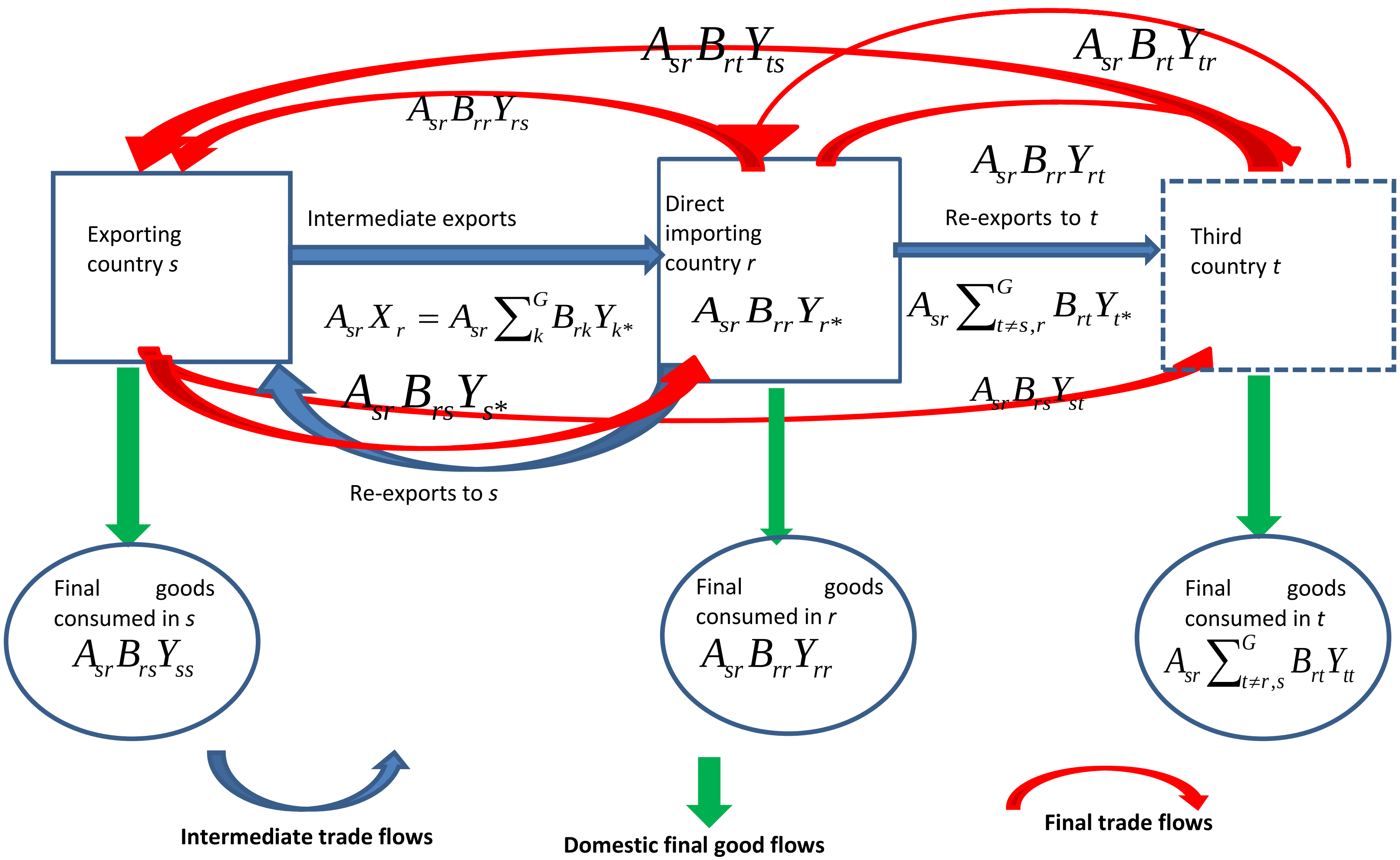
Inserting equation (A11) into the last term of equation (A10), the gross intermediate exports of country s to country r can be fully decomposed according to where they are absorbed:

$$\begin{aligned} A^{sr} X^{r} &= \sum_{r \neq s}^{G} A^{sr} B^{rr} Y^{rr} + \sum_{r \neq s}^{G} A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{tt} + \sum_{r \neq s}^{G} A^{sr} B^{rr} \sum_{t \neq s}^{G} Y^{rt} + \sum_{r \neq s}^{G} A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{tr} \\ &+ \sum_{r \neq s}^{G} A^{sr} \sum_{t \neq s,r}^{G} B^{rt} \sum_{u \neq s,r,t}^{G} Y^{tu} + \sum_{r \neq s}^{G} A^{sr} \sum_{t \neq s}^{G} B^{rt} Y^{ts} + \sum_{r \neq s}^{G} A^{sr} B^{rs} Y^{ss} + \sum_{r \neq s}^{G} A^{sr} B^{rs} Y^{sr} + \sum_{r \neq s}^{G} A^{sr} B^{rs} \sum_{t \neq s,r}^{G} Y^{st} \end{aligned} \tag{A12}$$

This decomposition is intuitively illustrated by figure A1.

After laying out the idea of how bilateral gross intermediate trade flows are decomposed, we provide a detailed step by step proof in a 3-country setting to simplify notation and make the materials accessible to more readers. Inserting equations (A10) and (A12) into the left hand of equation (19) in the main text, which defines domestic emissions embodied in gross exports from country s to country r based on forward industrial linkages, we obtain

Figure A1. **Accounting for gross bilateral intermediate trade flows between country *s* and country *r***



Source: improved from Wang, Wei and Zhu (2014) Learning about global value chains by looking beyond official trade data: Part 1. http://www.voxeu.org/article/learning-about-global-value-chains-looking-beyond-official-trade-data-part-1

$$
\begin{aligned}
&EEG\_F^{sr} = \hat{F}^{s} L^{ss} E^{sr} \\
&= \hat{F}^{s} L^{ss} Y^{sr} + \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rr} + L^{ss} A^{sr} B^{rt} Y^{tr} + L^{ss} A^{sr} B^{rs} Y^{sr} \right] \\
&+ \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rs} Y^{st} \right] \\
&+ \hat{F}^{s} \left[VL^{ss} A^{sr} B^{rr} Y^{rs} + L^{ss} A^{sr} B^{rt} Y^{ts} + L^{ss} A^{sr} B^{rs} Y^{ss} \right]
\end{aligned} \tag{A13}
$$

The 1st term, $\hat{F}^{s} L^{ss} Y^{sr}$, represents emissions generated by each industry of country *s* embodied in its final goods exports to country *r*. The 2nd-4th terms (the 1st bracket) are emissions generated by each industry of country *s* embodied in its intermediate exports to country *r* that are driven by final demand in country *r*. The 5th-7th terms (the 2nd bracket) are emissions generated by each industry of country *s* embodied in its intermediate exports to country *r* that are driven by final demand in third countries (*t*). The 8th-10th terms (the 3rd bracket) are emissions generated by each industry of country *s* embodied in its intermediate exports to country *r* that ultimately return and are driven by final demand in country *s*.

Based on equation (17) in the main text, EEX_F^{sr}, embodied emissions in exports from country *s* to country *r* based on forward industrial linkage in a three country world can be expressed as

$$
\begin{aligned}
&EEX\_F^{sr} = \hat{F}^{s} B^{ss} Y^{sr} + \hat{F}^{s} B^{sr} Y^{rr} + \hat{F}^{s} B^{st} Y^{tr} \\
&= \hat{F}^{s} \left[L^{ss} Y^{sr} + (B^{ss} - L^{ss}) Y^{sr} \right] + \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rr} + L^{ss} A^{st} B^{tr} Y^{rr} \right] \\
&+ \hat{F}^{s} \left[L^{ss} A^{sr} B^{rt} Y^{tr} + L^{ss} A^{st} B^{tt} Y^{tr} \right] = \hat{F}^{s} L^{ss} Y^{sr} + \hat{F}^{s} \left[L^{ss} A^{sr} B^{rs} Y^{sr} + L^{ss} A^{st} B^{ts} Y^{sr} \right] \\
&+ \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rr} + L^{ss} A^{st} B^{tr} Y^{rr} \right] + \hat{F}^{s} \left[L^{ss} A^{sr} B^{rt} Y^{tr} + L^{ss} A^{st} B^{tt} Y^{tr} \right]
\end{aligned} \tag{A14}
$$

Rearranging equation (A14) gives

$$
\begin{aligned}
&EEX\_F^{sr} = \hat{F}^{s} L^{ss} Y^{sr} + \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rr} + L^{ss} A^{sr} B^{rt} Y^{tr} + L^{ss} A^{sr} B^{rs} Y^{sr} \right] \\
&+ \hat{F}^{s} \left[L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr} \right]
\end{aligned} \tag{A15}
$$

Therefore,

$$
\begin{aligned}
&EEG\_F^{sr} - VAX\_F^{sr} = \hat{F}^{s} L^{ss} E^{sr} - \hat{F}^{s} B^{ss} Y^{sr} + \hat{F}^{s} B^{sr} Y^{rr} + \hat{F}^{s} B^{st} Y^{tr} \\
&= \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rs} + L^{ss} A^{sr} B^{rt} Y^{ts} + L^{ss} A^{sr} B^{rs} Y^{ss} \right] \\
&+ \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rs} Y^{st} \right] \\
&- \hat{F}^{s} \left[L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr} \right]
\end{aligned} \tag{A16}
$$

The 1st bracket of equation (A16) is emissions by industry embodied in the intermediate exports of country *s* to country *r* that are ultimately returned to satisfy final demand at home, which is the same as equation (18) in the main text in a three country world. We call it REE_F^{sr}:

$$
\begin{aligned}
REE\_F^{sr} &= \hat{F}^{s} L^{ss} A^{sr} B^{rr} Y^{rs} + \hat{F}^{s} L^{ss} A^{sr} B^{rt} Y^{ts} + \hat{F}^{s} L^{ss} A^{sr} B^{rs} Y^{ss} \\
&= \hat{F}^{s} L^{ss} A^{sr} \sum_{u}^{G} B^{ru} Y^{us}
\end{aligned} \tag{A17}
$$

The 2nd bracket in equation (A16) represents emissions by industry embodied in the intermediate exports from country *s* to country *r* that are driven by final demand in the third country (*t*). The 3rd bracket in equation (A16) represents emissions by industry embodied in the intermediate exports of country *s* to the third country (*t*) that are driven by final demand in country *r*. It is easy to understand that the 2nd and the 3rd brackets in equation (A16) are not equal to each other except very special cases. Therefore, neither EEG_F nor VLE based on forward linkage equals EEX_F + REE_F at bilateral and bilateral sector level.

However, summing up equation (A16) over all trade partners (i.e., countries *r* and *t* in the three country world), the terms in the 2nd bracket and the terms in the 3rd bracket will equal each other and cancel out:

$$
\begin{aligned}
&\left[\hat{F}^{s} L^{ss} E^{sr} - EEX\_F^{sr}\right] + \left[\hat{F}^{s} L^{ss} E^{st} - EEX\_F^{st}\right] \\
&= REE\_F^{sr} + \hat{F}^{s}\left[L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rs} Y^{st}\right] \\
&- \hat{F}^{s}\left[L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr}\right] \\
&+ REE\_F^{st} + \hat{F}^{s}\left[L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr}\right] \\
&- \hat{F}^{s}\left[L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rs} Y^{st}\right] \\
&= REE\_F^{sr} + REE\_F^{st}
\end{aligned} \tag{A18}
$$

Rearranging equation (A18) gives

$$
\begin{aligned}
EEG\_F^{sr} + EEG\_F^{st} &= \hat{F}^{s} L^{ss} E^{sr} + \hat{F}^{s} L^{ss} E^{st} \\
&= \left[EEX\_F^{sr} + REE\_F^{sr}\right] + \left[EEX\_F^{st} + REE\_F^{st}\right]
\end{aligned} \tag{A19}
$$

Therefore, EEG_F or VLE based on forward linkage are equal to EEX_F + REE_F at the country/sector and country aggregate levels. This proves that equation (20) in the main text holds.

A.3 Step by step proofs of Equations (25), (26) and (27) in the main text

Inserting equations (A10) and (A12) into the left hand side of equation (25) in the main text, which defines domestic emissions embodied in gross exports from country *s* to country *r* based on backward industrial linkages, we obtain the following equations for the three country world.

$$
\begin{aligned}
EEG\_B^{sr} &= (F^{s} L^{ss})^{T} \# E^{sr} = (F^{s} L^{ss})^{T} \# Y^{sr} + (F^{s} L^{ss})^{T} \# (A^{sr} B^{rr} Y^{rr} + A^{sr} B^{rt} Y^{tr} + A^{sr} B^{rs} Y^{sr}) \\
&+ (F^{s} L^{ss})^{T} \# (A^{sr} B^{rt} Y^{tt} + A^{sr} B^{rr} Y^{rt} + A^{sr} B^{rs} Y^{st}) \\
&+ (F^{s} L^{ss})^{T} \# (A^{sr} B^{rr} Y^{rs} + A^{st} B^{rt} Y^{ts} + A^{sr} B^{rs} Y^{ss})
\end{aligned} \tag{A20}
$$

This shows that EEG_B^{sr} can be decomposed into four parts: emissions embodied in final goods exports, emissions embodied in intermediate goods that are used to satisfy final demand in the direct importing country *r*, emissions embodied in intermediate exports returned to the exporting country *s*, and re-exported to third countries *t*. Emissions in these terms include emissions generated not only by the exporting sectors but also by other domestic sectors that contribute to the production of a particular sector's gross exports.

Based on equation (23) in the main text, EEX_B^{sr} can be expressed as

$$\begin{aligned} EEX\_B^{sr} &= (F^s B^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) + (F^s L^{ss})^T \# (A^{sr} B^{rt} Y^{tr}) \\ &+ (F^s L^{ss})^T \# (A^{st} B^{tr} Y^{rr}) + (F^s L^{ss})^T \# (A^{st} B^{tt} Y^{tr}) \end{aligned} \quad \text{(A21)}$$

where

$$\begin{aligned} (F^s B^{ss})^T \# Y^{sr} &= (F^s L^{ss})^T \# Y^{sr} + (F^s B^{ss} - F^s L^{ss})^T \# Y^{sr} \\ &= (F^s L^{ss})^T \# Y^{sr} + (F^s L^{ss} A^{sr} B^{rs})^T \# Y^{sr} + (F^s L^{ss} A^{st} B^{ts})^T \# Y^{sr} \end{aligned} \quad \text{(A22)}$$

Inserting equation (A22) into equation (A21) we obtain

$$\begin{aligned} EEX\_B^{sr} &= (F^s L^{ss})^T \# Y^{sr} + (F^s L^{ss} A^{sr} B^{rs})^T \# Y^{sr} + (F^s L^{ss} A^{st} B^{ts})^T \# Y^{sr} \\ &+ (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) + (F^s L^{ss})^T \# (A^{st} B^{tt} Y^{tr}) \\ &+ (F^s L^{ss})^T \# (A^{st} B^{tr} Y^{rr}) + (F^s L^{ss})^T \# (A^{sr} B^{rt} Y^{tr}) \end{aligned} \quad \text{(A23)}$$

Therefore

$$\begin{aligned} &(F^s L^{ss})^T \# E^{sr} - EEX\_B^{sr} \\ &= (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rs} + A^{sr} B^{rt} Y^{ts} + A^{sr} B^{rs} Y^{ss}) \\ &+ (F^s L^{ss})^T \# (A^{sr} B^{rt} Y^{tt} + A^{sr} B^{rr} Y^{rt} + A^{sr} B^{rs} Y^{st}) \\ &- [(F^s L^{ss})^T \# (A^{st} B^{tr} Y^{rr} + A^{st} B^{tt} Y^{tr}) + (F^s L^{ss} A^{st} B^{ts})^T \# Y^{sr}] \\ &+ [(F^s L^{ss})^T \# A^{sr} B^{rs} Y^{sr} - (F^s L^{ss} A^{sr} B^{rs})^T \# Y^{sr}] \end{aligned} \quad \text{(A24)}$$

The first term of equation (A24) represents the amount of emissions embodied in the sectoral exports from country *s* to country *r* that finally return home, and is exactly the same as equation (26) in the main text in a three country world:

$$REE\_B^{sr} = (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rs}) + (F^s L^{ss})^T \# (A^{sr} B^{rt} Y^{ts}) + (F^s L^{ss})^T \# (A^{sr} B^{rs} Y^{ss}) \quad \text{(A25)}$$

The second term of equation (A24) represents emissions in the sectoral intermediate exports of country *s* to country *r* which are then re-exported to other countries (both countries *r* and *s*) to produce final products that are consumed in the third country *t*. The third term of equation (A24) represents emissions in the gross intermediate exports of country *s* to third country *t* to produce final product exports to country *r* or produce intermediate products exports to countries *r* or *s* for production of final goods and services consumed in country *r*. As we will show later, $(F^s L^{ss})^T \# A^{sr} B^{rs} Y^{sr} = (F^s L^{ss} A^{sr} B^{rs})^T \# Y^{sr}$ at the bilateral aggregate level but not at the bilateral/sector level.

Therefore

$$\begin{aligned} & EEG\_B^{sr} - EEX\_B^{sr} - REE\_B^{sr} = (F^s L^{ss})^T \#(A^{sr} B^{rt} Y^{tt} + A^{sr} B^{rr} Y^{rt} + A^{sr} B^{rs} Y^{st}) \\ & + [(F^s L^{ss})^T \# A^{sr} B^{rs} Y^{sr} - (F^s L^{ss} A^{sr} B^{rs})^T \# Y^{sr}] \\ & - [(F^s L^{ss})^T \#(A^{st} B^{tr} Y^{rr} + A^{st} B^{tt} Y^{tr}) + (F^s L^{ss} A^{st} B^{ts})^T \# Y^{sr}] \neq 0 \end{aligned} \tag{A26}$$

It is obvious that the positive and negative terms in equation (A26) are not equal to each other except in very special cases. This indicates that EEG_B^{sr} and (EEX_B^{sr} +REE_ B^{sr}) cannot be equal each to other at the bilateral/sector level in general. At the bilateral aggregate level, summing (A26) over sectors, we obtain

$$\begin{aligned} & uEEG\_B^{sr} - uEEX\_B^{sr} - uREE\_B^{sr} = u(F^s L^{ss})^T \#(A^{sr} B^{rt} Y^{tt} + A^{sr} B^{rr} Y^{rt} + A^{sr} B^{rs} Y^{st}) \\ & - u(F^s L^{ss})^T \#(A^{st} B^{tr} Y^{rr} + A^{st} B^{tt} Y^{tr} + A^{st} B^{ts} Y^{sr}) \\ & = F^s (L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rs} Y^{st}) \\ & - F^s (L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr}) \neq 0 \end{aligned} \tag{A27}$$

The two terms in equation (A27) are still not equal each other in general. Therefore, the sum of $uEEX\_B^{sr}$ and $uREE\_B^{sr}$ does not equal $uEEG\_B^{sr}$ at the bilateral aggregate level.

Summing up equation (A27) over all trading partners *r* and *t*, the positive and negative terms will cancel out:

$$\begin{aligned} & uEEG\_B^{sr} + uEEG\_B^{st} - u(EEX\_B^{sr} - REE\_B^{sr} - EEX\_B^{st} - REE\_B^{st}) \\ & = F^s (L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rs} Y^{st}) \\ & - F^s (L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr}) \\ & + F^s (L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr}) \\ & - F^s (L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rs} Y^{st}) = 0 \end{aligned} \tag{A28}$$

Therefore, equation (27) in the main text holds.

$$\sum_{r \neq s}^{G} uEEG\_B^{sr} = \sum_{r \neq s}^{G} (uEEX\_B^{sr} + uREE\_B^{sr}) = \sum_{s \neq r}^{G} F^s L^{ss} E^{sr}$$

In a two-sector case,

$$
\begin{aligned}
&(F^{s}L^{ss})^{T}\#A^{sr}B^{rs}Y^{sr}-(F^{s}L^{ss}A^{sr}B^{rs})^{T}\#Y^{sr}\\
&=\begin{bmatrix} f_1^{s} & f_2^{s}\end{bmatrix}\begin{bmatrix} l_{11}^{ss} & l_{12}^{ss}\\ l_{21}^{ss} & l_{22}^{ss}\end{bmatrix}\#\begin{bmatrix} a_{11}^{sr} & a_{12}^{sr}\\ a_{12}^{sr} & a_{22}^{sr}\end{bmatrix}\begin{bmatrix} b_{11}^{rs} & b_{12}^{rs}\\ b_{21}^{rs} & b_{22}^{rs}\end{bmatrix}\begin{bmatrix} y_1^{sr}\\ y_2^{sr}\end{bmatrix}\\
&-\left\{\begin{bmatrix} f_1^{s} & f_2^{s}\end{bmatrix}\begin{bmatrix} l_{11}^{ss} & l_{12}^{ss}\\ l_{21}^{ss} & l_{22}^{ss}\end{bmatrix}\begin{bmatrix} a_{11}^{sr} & a_{12}^{sr}\\ a_{21}^{sr} & a_{22}^{sr}\end{bmatrix}\begin{bmatrix} b_{11}^{rs} & b_{12}^{rs}\\ b_{21}^{rs} & b_{22}^{rs}\end{bmatrix}\right\}\#\begin{bmatrix} y_1^{sr}\\ y_2^{sr}\end{bmatrix}\\
&=\begin{bmatrix} f_1^{s}l_{11}^{ss}+f_2^{s}l_{21}^{ss}\\ f_1^{s}l_{12}^{ss}+f_2^{s}l_{22}^{ss}\end{bmatrix}\#\begin{bmatrix} a_{11}^{sr}b_{11}^{rs}y_1^{sr}+a_{11}^{sr}b_{12}^{rs}y_2^{sr}+a_{12}^{sr}b_{21}^{rs}y_1^{sr}+a_{12}^{sr}b_{22}^{rs}y_2^{sr}\\ a_{21}^{sr}b_{11}^{rs}y_1^{sr}+a_{21}^{sr}b_{12}^{rs}y_2^{sr}+a_{22}^{sr}b_{21}^{rs}y_1^{sr}+a_{22}^{sr}b_{22}^{rs}y_2^{sr}\end{bmatrix}\\
&-\begin{bmatrix} f_1^{s}\sum_{i}^{2}l_{1i}^{ss}\sum_{j}^{2}a_{ij}^{sr}b_{j1}^{rs}+f_2^{s}\sum_{i}^{2}l_{2i}^{ss}\sum_{j}^{2}a_{ij}^{sr}b_{j1}^{rs}\\ f_1^{s}\sum_{i}^{2}l_{1i}^{ss}\sum_{j}^{2}a_{ij}^{sr}b_{j2}^{rs}+f_2^{s}\sum_{i}^{2}l_{2i}^{ss}\sum_{j}^{2}a_{ij}^{sr}b_{j2}^{rs}\end{bmatrix}\#\begin{bmatrix} y_1^{sr}\\ y_2^{sr}\end{bmatrix}\\
&=\begin{bmatrix} \sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}\sum_{k}^{2}b_{jk}^{rs}y_k^{sr}\\ \sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}\sum_{k}^{2}b_{jk}^{rs}y_k^{sr}\end{bmatrix}-\begin{bmatrix} \sum_{i}^{2}f_i^{s}\sum_{j}^{2}l_{ij}^{ss}\sum_{k}^{2}a_{jk}^{sr}b_{k1}^{rs}y_1^{sr}\\ \sum_{i}^{2}f_i^{s}\sum_{j}^{2}l_{ij}^{ss}\sum_{k}^{2}a_{jk}^{sr}b_{k2}^{rs}y_2^{sr}\end{bmatrix}\\
&=\begin{bmatrix} \sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}b_{j2}^{rs}y_2^{sr}-\sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}b_{j1}^{rs}y_1^{sr}\\ \sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}b_{j1}^{rs}y_1^{sr}-\sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}b_{j2}^{rs}y_2^{sr}\end{bmatrix}\neq\begin{bmatrix}0\\0\end{bmatrix}
\end{aligned}
\tag{A29}
$$

However,

$$
\begin{aligned}
&u(F^{s}L^{ss})^{T}\#A^{sr}B^{rs}Y^{sr}-u(F^{s}L^{ss}A^{sr}B^{rs})^{T}\#Y^{sr}\\
&=\begin{bmatrix}1 & 1\end{bmatrix}\begin{bmatrix} \sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}b_{j2}^{rs}y_2^{sr}-\sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}b_{j1}^{rs}y_1^{sr}\\ \sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}b_{j1}^{rs}y_1^{sr}-\sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}b_{j2}^{rs}y_2^{sr}\end{bmatrix}=0
\end{aligned}
\tag{A30}
$$

Both elements in the last term in (A29) are not equal to zero in general. However, after aggregating over sectors, the two elements will cancel each other, as shown in equation (A30) Therefore, summing up equation (A26) over all trading partners *r* and *t*, but not over sectors, the positive and negative terms will not cancel out, as in equation (A27). This means $\sum_{r\neq s}^{G}EEG\_B^{sr}$ is also not equal to the sum of $\sum_{r\neq s}^{G}EEX\_B^{sr}$ and $\sum_{r\neq s}^{G}REE\_B^{sr}$ at the country-sector level.

Appendix B Additional results

B1 Who emits CO_2 emissions for whom

Table B1 shows how much some selected large countries' CO_2 emissions are induced by different sources of final demand through different routes of supply chains for both 1995 and 2009. From the upper part of Table B1 we see that China's total production-based CO_2 emissions experienced the largest increase (128%) from 2,723,066 kt in 1995 to 6,213,385 kt followed by India (108%) and the rest of the world (RoW, 37%)[13]. For all developed countries, their production-based CO_2 emissions decreased, especially for Germany which had the largest decrease of 12%.

Total production-based CO_2 emissions can be decomposed into 5 parts (referring to Figure 1) according to sources of final demand satisfied. The structure and changing pattern among these five final demand sources between 1995 and 2009 are shown in the middle and bottom parts of Table B1. Obviously, for all selected countries and for both years, the CO_2 emissions generated by the domestic production of goods and services that sell directly in the domestic market (EH_F) account for the majority of the total emissions, especially for countries with relatively large economic size. This is not surprising because most large countries' production is mainly for domestic use. The interesting thing is that the share of the remaining 4 sources shows a very different pattern across countries. For example, in both 1995 and 2009, the share of China's CO_2 emissions generated by its production of final goods exports (EEX_F1) is the largest when compared to the other selected countries. This implies that China's participation in GVCs is mainly through providing final goods exports and, naturally, relatively more CO_2 emissions are generated by this route. In contrast, Russia's CO_2 emissions generated by foreign final demand are mainly from providing intermediate goods exports (EEX_F2 + EEX_F3). This phenomenon clearly illustrates that a country's production-based CO_2 emissions depend not only on the energy efficiency of its production technology, but also on its position and participation in GVCs. Both Germany and UK have a large portion of their production-based CO_2 emissions that are generated by the production of exports to meet foreign final demand, as China does, but with a much higher portion of such emissions generated by the production of intermediate exports. When looking at the changing pattern of the shares between 1995 and 2009 (the bottom right part of Table B1), for most countries except India, EH_F decreased, while other parts normally increased. This reflects the fact that most countries have been involved in GVCs and more of their emissions

[13]The RoW here is not the rest of the selected countries shown in Table 1; it's the original country group of the RoW used in WIOD regarded as a group of all the other developing countries not covered by WIOD.

production is for satisfying final demands in foreign countries. In particular, the increase in the share for EEX_F2 is about 61% (from 9.1% to 14.7%) for China, and 63% (from 13.0% to 21.3%) for Germany. Since both countries have been the main supply hub of intermediate manufacturing goods in international trade, a relatively large portion of CO_2 emissions are naturally generated by this route. The share for EEX_F3 (emissions generated by the production of intermediates that re-exported to third countries) is lower than EEX_F1 and EEX_F2, while its rate of change for all countries is positive and very large. This clearly reflects the increasing complexity of GVCs, since more intermediate goods and services cross national borders more than once and are re-exported to third countries for further processing in the global production networks. In addition, the share for REE_F also experienced a dramatic increase for all selected developing countries, such as China (592%), India (294%) and the RoW (123%), although the absolute level of this share is extremely low. This implies that the final goods imported by China tend to embody more emissions generated by its own intermediate goods exports given its increasing presence in international production networks.

Table B1 CO_2 emissions by sources of final demand (forward industrial-linkage-based decomposition, corresponding to Figure 1)

	1995						2009					
CO2 Emissions (KT)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	2,126,639	3,196	301,045	249,125	43,061	2,723,066	4,191,734	50,471	891,922	913,035	166,223	6,213,385
IND	607,263	165	39,284	65,961	8,154	720,827	1,266,226	1,356	95,723	116,290	22,214	1,501,809
JPN	874,562	3,068	43,965	90,214	12,458	1,024,267	753,151	3,223	47,700	124,446	25,217	953,737
USA	3,869,470	38,148	142,285	262,327	29,954	4,342,184	3,719,713	29,436	136,290	264,124	38,152	4,187,715
GBR	316,770	2,228	42,859	75,658	13,517	451,032	285,484	2,015	40,381	79,426	14,991	422,297
DEU	542,851	7,014	61,628	94,494	18,717	724,704	383,503	7,692	81,929	135,490	27,695	636,309
RUS	974,488	3,278	48,382	326,921	59,269	1,412,338	926,130	3,731	34,581	360,665	85,379	1,410,486
RoW	2,626,249	30,223	218,217	442,696	59,812	3,377,197	3,341,296	92,569	292,962	784,936	129,232	4,640,995
Share (%)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	78.1%	0.1%	11.1%	9.1%	1.6%	100.0%	67.5%	0.8%	14.4%	14.7%	2.7%	100.0%
IND	84.2%	0.0%	5.4%	9.2%	1.1%	100.0%	84.3%	0.1%	6.4%	7.7%	1.5%	100.0%
JPN	85.4%	0.3%	4.3%	8.8%	1.2%	100.0%	79.0%	0.3%	5.0%	13.0%	2.6%	100.0%
USA	89.1%	0.9%	3.3%	6.0%	0.7%	100.0%	88.8%	0.7%	3.3%	6.3%	0.9%	100.0%
GBR	70.2%	0.5%	9.5%	16.8%	3.0%	100.0%	67.6%	0.5%	9.6%	18.8%	3.5%	100.0%
DEU	74.9%	1.0%	8.5%	13.0%	2.6%	100.0%	60.3%	1.2%	12.9%	21.3%	4.4%	100.0%
RUS	69.0%	0.2%	3.4%	23.1%	4.2%	100.0%	65.7%	0.3%	2.5%	25.6%	6.1%	100.0%
RoW	77.8%	0.9%	6.5%	13.1%	1.8%	100.0%	72.0%	2.0%	6.3%	16.9%	2.8%	100.0%
Change rate between 1995 and 2009	Change rate of CO2 emisions between 1995 and 2009						Change rate of shares between 1995 and 2009					
	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	97%	1479%	196%	266%	286%	128%	−14%	592%	30%	61%	69%	
IND	109%	722%	144%	76%	172%	108%	0%	294%	17%	−15%	31%	
JPN	−14%	5%	8%	38%	102%	−7%	−8%	13%	17%	48%	117%	
USA	−4%	−23%	−4%	1%	27%	−4%	0%	−20%	−1%	4%	32%	
GBR	−10%	−10%	−6%	5%	11%	−6%	−4%	−3%	1%	12%	18%	
DEU	−29%	10%	33%	43%	48%	−12%	−20%	25%	51%	63%	69%	
RUS	−5%	14%	−29%	10%	44%	0%	−5%	14%	−28%	10%	44%	
RoW	27%	206%	34%	77%	116%	37%	−7%	123%	−2%	29%	57%	

B2 CO_2 emissions generated in domestic and foreign segments of global supply chains

As shown in Figure 2, a country's CO_2 emissions can also be traced along global supply chains in terms of different types of energy source by using the backward industrial-linkage-based decomposition technique. Table B2 shows the decomposition results at the national level (sector aggregation) for selected countries for 1995 and 2009. In absolute terms, in 1995, the US's production of final products, no matter whether they are used domestically or internationally, generates massive amount of CO_2 emissions (4,423,852 kt). The US is followed by the RoW (3,382,085 kt) and China (2,513,050 kt). This depends both on a country's economic size and on its energy efficiency. In 2009, the situation changed dramatically: with a 125% increase compared to 1995, China becomes the largest emitter, followed by the RoW, the US and India. When looking at the share (the middle part of Table B3), we can see that CO_2 emissions generated in domestic segments of global supply chains accounts for the majority of total induced CO_2 emissions for all selected countries. This can be easily understood since, for most countries, their upstream supply chains are mainly located at home. However, the difference of the share across countries is still significant. For example, more than 20% of CO_2 emissions from Japan's, the UK and Germany's production of final products are generated in foreign segments of global supply chains in 1995. This clearly reflects at least two facts: one is that these countries' supply chains need more foreign intermediate inputs for producing final products, and the other is that much higher CO_2 emission intensity is located in foreign segments of their global supply chains than for the other selected developing countries.

The structure of energy use for producing final products in global supply chains varies across countries. China's and India's CO_2 emissions generated in their domestic supply chains are mainly from the use of coal (76.0% and 64.1% respectively in 1995). This depends not only on their relatively rich endowment of coal, but also on the higher CO_2 emission intensity in production processes using coal. This can also be indirectly confirmed by the fact that most of the CO_2 emissions generated in the foreign segment of Japan's supply chains were from coal in 2009, since most of its foreign upstream industries are located in China, which provides intermediate products mainly by using coal-based energy.

When looking at the pattern of structure changes between 1995 and 2009 (the bottom part of Table B2), some important features emerge. 1) For all selected countries, the share of CO_2 emissions generated in the domestic segment of their global supply chains declined, especially for China (-6.4%), England (-7.1%), Germany (-7.9%), and the RoW (-8.7%). On the other hand, the share of their foreign segments increased dramatically, especially for China (186%). Since countries tend to use more intermediate imports to make final goods, given the reduction in international trade costs, naturally more CO_2 emissions are generated in foreign segments of supply chains. 2) The share of coal, petroleum, and other energy-based CO_2 emissions generated in the domestic segment decreased, while natural gas and waste-based CO_2 emissions increased between 1995 and 2009. This reflects the fact that more countries are shifting to the usage of relatively low carbon intensity energy in the domestic part of their final goods production. Japan is the only exception, its coal-based CO_2 emissions in domestic segment increased 32.0 % from 1995 to 2009. This is mainly because Japan's energy efficiency is higher even if using coal to generate energy rather than thermal power generation; at the same time, it's cheaper to import coal from neighboring countries, like China which is a coal-rich country. 3) For almost all emission sources, their shares of CO_2 emissions in the foreign segment for all selected countries increased significantly between 1995 and 2009. In this regard, China's change is the most remarkable. This is mainly because China has been both the largest final goods assembler and a producer which also needs to import more components and intermediate inputs produced by foreign countries.

Table B2 CO_2 emissions to produce a final goods and services in global supply chains (backward industrial-linkage-based decomposition, corresponding to Figure 2)

1995	CO2 emissions generated by domestic segment of GVC						CO2 emissions generated by foreign segment of GVC							Change rate between 1995 and 2009
CO2 emissions (Kt)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal	Total	
CHN	1,911,062	293,157	38,157	–	187,373	2,429,749	23,052	31,061	18,937	386	9,865	83,301	2,513,050	
IND	439,230	139,432	24,262	–	43,743	646,667	11,451	12,235	9,829	174	5,027	38,716	685,383	
JPN	236,609	484,494	125,142	2,703	71,315	920,263	95,738	96,867	53,407	664	29,841	276,517	1,196,780	
USA	1,641,832	1,421,481	731,322	35,302	198,759	4,028,696	120,695	139,960	85,996	1,332	47,173	395,156	4,423,852	
GBR	139,308	116,119	71,457	1,191	32,567	360,642	37,565	41,270	24,354	786	10,758	114,733	475,375	
DEU	307,303	197,880	87,580	8,777	6,097	607,637	84,962	73,667	62,218	2,475	27,492	250,814	858,451	
RUS	260,885	215,568	451,172	9,283	87,242	1,024,150	7,602	7,172	4,209	178	3,297	22,458	1,046,608	
RoW	614,637	1,393,462	639,832	3,633	210,533	2,862,097	162,491	232,758	77,264	2,158	45,317	519,988	3,382,085	
Share (%)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal	Total	
CHN	76.0%	11.7%	1.5%	0.0%	7.5%	96.7%	0.9%	1.2%	0.8%	0.0%	0.4%	3.3%	100.0%	
IND	64.1%	20.3%	3.5%	0.0%	6.4%	94.4%	1.7%	1.8%	1.4%	0.0%	0.7%	5.6%	100.0%	
JPN	19.8%	40.5%	10.5%	0.2%	6.0%	76.9%	8.0%	8.1%	4.5%	0.1%	2.5%	23.1%	100.0%	
USA	37.1%	32.1%	16.5%	0.8%	4.5%	91.1%	2.7%	3.2%	1.9%	0.0%	1.1%	8.9%	100.0%	
GBR	29.3%	24.4%	15.0%	0.3%	6.9%	75.9%	7.9%	8.7%	5.1%	0.2%	2.3%	24.1%	100.0%	
DEU	35.8%	23.1%	10.2%	1.0%	0.7%	70.8%	9.9%	8.6%	7.2%	0.3%	3.2%	29.2%	100.0%	
RUS	24.9%	20.6%	43.1%	0.9%	8.3%	97.9%	0.7%	0.7%	0.4%	0.0%	0.3%	2.1%	100.0%	
RoW	18.2%	41.2%	18.9%	0.1%	6.2%	84.6%	4.8%	6.9%	2.3%	0.1%	1.3%	15.4%	100.0%	
2009	CO2 emissions generated by domestic segment of GVC						CO2 emissions generated by foreign segment of GVC						Total	
CO2 emissions (Kt)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal		
CHN	4,098,564	552,773	142,473	0	326,088	5,119,898	161,716	170,108	146,806	3,421	54,990	537,041	5,656,939	125%
IND	952,788	244,857	79,460	0	85,728	1,362,833	57,762	36,723	32,685	510	13,875	141,555	1,504,388	119%
JPN	274,427	306,539	168,896	7,356	45,322	802,540	101,801	73,519	53,700	749	19,254	249,023	1,051,563	−12%
USA	1,632,018	1,259,978	798,603	53,355	126,083	3,870,037	238,903	160,596	136,688	2,075	55,471	593,733	4,463,770	1%
GBR	89,744	85,842	101,247	3,575	46,391	326,799	51,785	41,930	31,504	1,254	10,389	136,862	463,661	−2%
DEU	214,441	146,990	85,506	21,330	278	468,545	98,039	67,708	57,925	2,050	24,767	250,489	719,034	−16%
RUS	197,522	174,079	468,240	12,910	109,339	962,090	15,567	9,588	5,938	277	3,671	35,041	997,131	−5%
RoW	761,424	1,644,039	1,048,100	6,930	230,144	3,690,637	455,449	395,188	155,364	6,249	72,088	1,084,338	4,774,975	41%
Share (%)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal	Total	
CHN	72.5%	9.8%	2.5%	0.0%	5.8%	90.5%	2.9%	3.0%	2.6%	0.1%	1.0%	9.5%	100.0%	
IND	63.3%	16.3%	5.3%	0.0%	5.7%	90.6%	3.8%	2.4%	2.2%	0.0%	0.9%	9.4%	100.0%	
JPN	26.1%	29.2%	16.1%	0.7%	4.3%	76.3%	9.7%	7.0%	5.1%	0.1%	1.8%	23.7%	100.0%	
USA	36.6%	28.2%	17.9%	1.2%	2.8%	86.7%	5.4%	3.6%	3.1%	0.0%	1.2%	13.3%	100.0%	
GBR	19.4%	18.5%	21.8%	0.8%	10.0%	70.5%	11.2%	9.0%	6.8%	0.3%	2.2%	29.5%	100.0%	
DEU	29.8%	20.4%	11.9%	3.0%	0.0%	65.2%	13.6%	9.4%	8.1%	0.3%	3.4%	34.8%	100.0%	
RUS	19.8%	17.5%	47.0%	1.3%	11.0%	96.5%	1.6%	1.0%	0.6%	0.0%	0.4%	3.5%	100.0%	
RoW	15.9%	34.4%	21.9%	0.1%	4.8%	77.3%	9.5%	8.3%	3.3%	0.1%	1.5%	22.7%	100.0%	
Change rate of the share between 1995 and 2009 (%)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal	Total	
CHN	−4.7%	−16.2%	65.9%		−22.7%	−6.4%	211.6%	143.3%	244.4%	293.7%	147.6%	186.4%	0.0%	
IND	−1.2%	−20.0%	49.2%		−10.7%	−4.0%	129.8%	36.7%	51.5%	33.5%	25.7%	66.6%	0.0%	
JPN	32.0%	−28.0%	53.6%	209.7%	−27.7%	−0.7%	21.0%	−13.6%	14.4%	28.4%	−26.6%	2.5%	0.0%	
USA	−1.5%	−12.2%	8.2%	49.8%	−37.1%	−4.8%	96.2%	13.7%	57.5%	54.4%	16.5%	48.9%	0.0%	
GBR	−34.0%	−24.2%	45.3%	207.8%	46.0%	−7.1%	41.3%	4.2%	32.6%	63.6%	−1.0%	22.3%	0.0%	
DEU	−16.7%	−11.3%	16.6%	190.1%	−94.6%	−7.9%	37.8%	9.7%	11.2%	−1.1%	7.6%	19.2%	0.0%	
RUS	−20.5%	−15.2%	8.9%	46.0%	31.5%	−1.4%	114.9%	40.3%	48.1%	63.3%	16.9%	63.8%	0.0%	
RoW	−12.3%	−16.4%	16.0%	35.1%	−22.6%	−8.7%	98.5%	20.3%	42.4%	105.1%	12.7%	47.7%	0.0%	

B3 CO_2 emissions induced by the production of gross exports for selected countries

As shown in Figure 3, when applying the backward industrial-linkage-based decomposition technique, it will identify who emits CO_2 emissions for whom to what extent in the production of gross exports. Table B3 represents the decomposition results for selected countries at the national level for both 1995 and 2009. In absolute terms, the RoW's gross exports induce the largest amount of CO2 emissions (869,561 kt) in 1995 followed by China (717,838 kt) and the US (531,191 kt). The total CO_2 emissions can be separated into domestic and foreign parts. The majority of induced CO_2 emissions in producing exports were from the domestic side for all selected countries. However, if a country, in producing exports, has a relatively large part of the upstream production process outside its territory the share of foreign CO_2 emissions could be large, as for Germany (33%), England (24%) and Japan (20%). Both the domestic part and the foreign part can be further divided into 4 parts, each based on different supply chain routes and types of final consumer. Obviously, in 1995, 97% of CO_2 emissions embodied in China's gross exports is from the domestic side, in which 49% is for fulfilling final demand of trading partners who directly import goods from China; 35% is for fulfilling China's trading partners' demands for intermediate inputs in their production of domestically consumed goods and services; 13% is for fulfilling third countries' final demands by providing intermediate goods to China's trading partners for their production of exports to third countries; just 1% is for fulfilling China's own final demand by re-importing what has been exported. For most countries, except China, their domestic CO_2 emissions embodied in gross exports come mainly through trade in intermediate goods (parts 2, 3, 4). For Part 4, the figure for the US is larger than the other countries. This is mainly because the US re-imports a relatively large part of its own intermediate goods that have first been exported to global supply chains. For the foreign CO_2 emissions in producing gross exports, Germany shows the largest figure, in which parts 7 and 8 account for 17% and 15%, respectively. This indicates that 17% of the total CO_2 emissions embodied in Germany's gross exports is from third countries which export intermediate goods to Germany for Germany's further production of final goods for export to its trading partners. On the other hand, 15% of the total CO_2 emissions embodied in Germany's gross exports is from third countries that export intermediate goods to Germany, which uses these goods to produce further intermediate goods and exports to its trading partners for making domestically consumed final goods and services. Part 5 shows the CO_2 emissions induced in Germany's trading partner countries that provide intermediate goods to Germany for its production of final goods which are finally consumed in its trading partner countries. Part 6 shows the CO_2 emissions induced in Germany's trading partners which provide intermediate goods to Germany for further processing into intermediate exports, which are imported by Germany's trading partners for producing domestically used final goods and services. Together parts 5 and 6 account for just 1%, since this kind of feedback effect in international production networks is normally small.

In order to investigate the structural changes of gross-export-based CO_2 emissions between 1995 and 2009 across different routes, we calculate the rate of change for both the absolute CO_2 emissions figure and the corresponding share and show the results in the bottom two parts of Table B3. We see the following three features. 1) The induced CO_2 emissions in gross exports for all developing countries, such as China (262%), India (128%), and the RoW (85%), experienced a more rapid increase than developed countries. Given the decreasing CO_2 intensity, both for developing countries and developed countries from 1995 to 2009, the most important driving factor for this change should be the rapid increase of gross exports produced by developing countries. For England and the USA, there are only 1% and 5% increases, respectively. Japan and Germany also experienced 37% and 48% increases, respectively. Although both of them have been service oriented economies, they still play an important role as two large trade hubs of intermediate goods in global supply chains. 2) When looking at the change of share, we see that the share of domestic CO_2 emissions in producing exports decreased for all countries, while the share of foreign CO_2 emissions increased for most countries, except England. This indirectly reflects the fact that most countries are getting to use more intermediate imports to produce their exports. As a result, relatively more CO_2 emissions are induced internationally rather than domestically in producing exports. 3) Looking at the changing pattern for each part, we see that parts 3, 7 and 8 have a relatively large absolute share and also show a positive change of their shares between 1995 and 2009. Therefore, these parts can be considered the main leading factors that cause both the increase in the absolute emissions and the share of total gross-export-based CO_2 emissions for all countries. All these three parts are related to the third country effects in our decomposition. This implies that the increasing complexity of specific routes in global supply chains is often associated with a corresponding increase of CO_2 emissions.

Table B3 CO_2 emissions in the production of gross exports (backward industrial-linkage-based decomposition, corresponding to Figure 3)

	1995										
CO2 emissions (KT)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in producing exports					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	301,045	214,501	77,685	3,196	596,427	1,241	940	12,392	6,839	21,411	617,838
IND	39,284	58,469	15,646	165	113,563	211	335	2,117	2,537	5,200	118,763
JPN	43,965	78,316	24,356	3,068	149,705	1,933	3,015	14,999	18,493	38,439	188,144
USA	142,285	228,543	63,738	38,148	472,714	3,176	4,034	25,195	26,072	58,477	531,191
GBR	42,859	61,174	28,001	2,228	134,262	1,784	1,973	20,562	17,855	42,174	176,436
DEU	61,628	76,173	37,038	7,014	181,853	2,924	2,586	45,228	40,108	90,846	272,700
RUS	48,382	260,126	126,064	3,278	437,850	85	286	993	3,679	5,043	442,893
RoW	218,217	382,331	120,177	30,223	750,948	5,530	5,760	50,908	56,416	118,613	869,561
Share (%)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in supplying imported inputs					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	49%	35%	13%	1%	97%	0%	0%	2%	1%	3%	100%
IND	33%	49%	13%	0%	96%	0%	0%	2%	2%	4%	100%
JPN	23%	42%	13%	2%	80%	1%	2%	8%	10%	20%	100%
USA	27%	43%	12%	7%	89%	1%	1%	5%	5%	11%	100%
GBR	24%	35%	16%	1%	76%	1%	1%	12%	10%	24%	100%
DEU	23%	28%	14%	3%	67%	1%	1%	17%	15%	33%	100%
RUS	11%	59%	28%	1%	99%	0%	0%	0%	1%	1%	100%
RoW	25%	44%	14%	3%	86%	1%	1%	6%	6%	14%	100%
	2009										
CO2 emissions (KT)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in producing exports					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	891,922	764,257	315,000	50,471	2,021,650	16,375	15,473	109,535	75,942	217,325	2,238,975
IND	95,723	92,687	45,817	1,356	235,583	2,634	2,029	21,564	9,298	35,524	271,107
JPN	47,700	98,451	51,212	3,223	200,586	3,276	7,268	19,022	27,921	57,487	258,073
USA	136,290	220,410	81,866	29,436	468,002	5,376	7,886	36,705	39,913	89,880	557,881
GBR	40,381	62,046	32,372	2,015	136,814	1,592	2,249	19,409	18,977	42,227	179,040
DEU	81,929	105,433	57,752	7,692	252,806	5,599	6,615	75,059	63,183	150,456	403,262
RUS	34,581	254,843	191,202	3,731	484,356	143	591	919	4,147	5,800	490,157
RoW	292,962	658,916	255,252	92,569	1,299,699	8,670	18,993	120,711	157,417	305,791	1,605,490
Share (%)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in supplying imported inputs					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	40%	34%	14%	2%	90%	1%	1%	5%	3%	10%	100%
IND	35%	34%	17%	1%	87%	1%	1%	8%	3%	13%	100%
JPN	18%	38%	20%	1%	78%	1%	3%	7%	11%	22%	100%
USA	24%	40%	15%	5%	84%	1%	1%	7%	7%	16%	100%
GBR	23%	35%	18%	1%	76%	1%	1%	11%	11%	24%	100%
DEU	20%	26%	14%	2%	63%	1%	2%	19%	16%	37%	100%
RUS	7%	52%	39%	1%	99%	0%	0%	0%	1%	1%	100%
RoW	18%	41%	16%	6%	81%	1%	1%	8%	10%	19%	100%
	Between 1995 and 2009										
Chage rate of CO2 emisions (%)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in supplying imported inputs					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	196%	256%	305%	1479%	239%	1220%	1547%	784%	1010%	915%	262%
IND	144%	59%	193%	722%	107%	1151%	506%	919%	266%	583%	128%
JPN	8%	26%	110%	5%	34%	69%	141%	27%	51%	50%	37%
USA	−4%	−4%	28%	−23%	−1%	69%	95%	46%	53%	54%	5%
GBR	−6%	1%	16%	−10%	2%	−11%	14%	−6%	6%	0%	1%
DEU	33%	38%	56%	10%	39%	91%	156%	66%	58%	66%	48%
RUS	−29%	−2%	52%	14%	11%	69%	106%	−7%	13%	15%	11%
RoW	34%	72%	112%	206%	73%	57%	230%	137%	179%	158%	85%
Chage rate of share (%)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in supplying imported inputs					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	−18%	−2%	12%	336%	−6%	264%	354%	144%	206%	180%	
IND	7%	−31%	28%	260%	−9%	448%	165%	346%	61%	199%	
JPN	−21%	−8%	53%	−23%	−2%	24%	76%	−8%	10%	9%	
USA	−9%	−8%	22%	−27%	−6%	61%	86%	39%	46%	46%	
GBR	−7%	0%	14%	−11%	0%	−12%	12%	−7%	5%	−1%	
DEU	−10%	−6%	5%	−26%	−6%	29%	73%	12%	7%	12%	
RUS	−35%	−11%	37%	3%	0%	53%	87%	−16%	2%	4%	
RoW	−27%	−7%	15%	66%	−6%	−15%	79%	28%	51%	40%	

B4 The potential environmental cost of value-added trade

As mentioned in the second section, following the proposed decomposition frameworks, both value-added and embodied emissions can be traced at the same time. When dividing the induced value added by induced CO_2 emissions, the potential environmental cost can be easily obtained. As an example, we apply this idea to the forward industrial-linkage-based decomposition (Figure 1) to show the relationship between trade in value added and trade in CO_2 emissions.

Table B4 The potential environmental cost of trade in value added (using forward industrial-linkage-based decomposition)

	1995					
CO2 emissions/value-added (KT/Million US$)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	3.6	4.6	3.9	4.6	4.3	3.7
IND	1.8	3.5	2.5	3.4	3.1	1.9
JPN	0.2	0.4	0.3	0.4	0.3	0.2
USA	0.6	0.7	0.7	0.7	0.7	0.6
GBR	0.4	0.6	0.5	0.6	0.6	0.4
DEU	0.3	0.4	0.3	0.4	0.4	0.3
RUS	3.9	5.9	4.2	6.0	6.4	4.4
RoW	1.0	1.5	1.4	1.4	1.5	1.1
	2009					
CO2 emissions/value-added (KT/Million US$)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	2.1	2.8	2.3	2.7	2.6	2.2
IND	1.6	2.7	1.8	2.2	2.3	1.6
JPN	0.2	0.4	0.3	0.4	0.3	0.2
USA	0.4	0.5	0.5	0.5	0.5	0.4
GBR	0.2	0.4	0.4	0.4	0.4	0.3
DEU	0.2	0.3	0.2	0.3	0.3	0.2
RUS	2.4	4.3	3.0	4.1	4.1	2.8
RoW	0.8	1.0	1.1	1.0	1.1	0.8
	between 1995 and 2009					
Change rate (%)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	−41%	−40%	−40%	−42%	−40%	−40%
IND	−13%	−24%	−28%	−35%	−23%	−16%
JPN	−13%	−4%	0%	0%	2%	−8%
USA	−31%	−27%	−23%	−29%	−29%	−31%
GBR	−33%	−36%	−9%	−33%	−34%	−31%
DEU	−32%	−24%	−22%	−24%	−27%	−26%
RUS	−39%	−27%	−29%	−31%	−35%	−36%
RoW	−25%	−34%	−24%	−29%	−27%	−24%

The main results are shown in Table B4. In general, the environmental cost for producing domestic value added without international trade (referring to EH_F) for all countries is lower than that of producing domestic value added through international trade. This implies that the value-added gain by international trade may be through a high-carbon process, which indirectly reflects the fact of carbon leakage across countries due to trade. At the country level, Russia shows the highest environmental cost (4.4 kt/million US$) followed by China (3.7 kt/million US$) in 1995, which are, respectively 18.5 and 22.0, times more costly than Japan (0.2 kt/million US$). In 2009, for all countries, a cost decrease can be observed, especially for China (-40%) and Russia (-36%). Energy efficiency changes and emissions-related regulation conducted both domestically and internationally can be considered as the main driving factors of this cost decline. However, the situation regarding carbon leakage shows no significant change, since the environmental cost for getting value added by international trade is still higher than that for pure domestic production in 2009.

B5 CO_2 emissions generated in the foreign segment of global supply chains by specific products

The backward industrial-linkage-based decomposition technique can help us trace the CO_2 emissions in supply chains at the detailed sector level for production of a specific final good in a particular country. As an example, Figure B1 shows the foreign sectors with the largest CO_2 emissions (top 30 out of 1435 sectors across all WIOD countries) in China's and Germany's Transportation Equipment supply chains for both 1995 and 2009. The major features can be summarized as follows. 1) The most intensive emitters of upstream countries in both countries' Transportation Equipment supply chains are from their neighboring countries. This is not surprising, since parts and components for producing cars follow the so-called just-in-time production system and trade costs across countries is one of the most important factors that affect the choice of production locations. It is, therefore, reasonable to build supply chains regionally rather than globally. 2) For both China and Germany, the most intensive foreign sector emitters in their Transportation Equipment supply chains are sectors 17 (Electricity, Gas and Water Supply), 12 (Basic Metals and Fabricated Metal), 9 (Chemicals and Chemical Products), and 2 (Mining and Quarrying). This depends on how close and strong the upstream sector links with the final product of transportation equipment, as well as the intensity of the CO_2 emissions arising from the production of parts and components directly and indirectly in the relevant upstream sectors. 3) Dramatic changes occur in the rankings of upstream countries and sectors during the 15 year sample period. This reflects the evolution of competitiveness not only in the quality and price of an upstream country or sector's intermediate goods in supply chains, but also on their energy efficiency. 4) The foreign segments in German car production are greener than those of China

Figure B1 Foreign sectoral CO_2 emissions (top 30 sectors) induced by a specific country's production of final goods (Transportation Equipment) in global supply chains

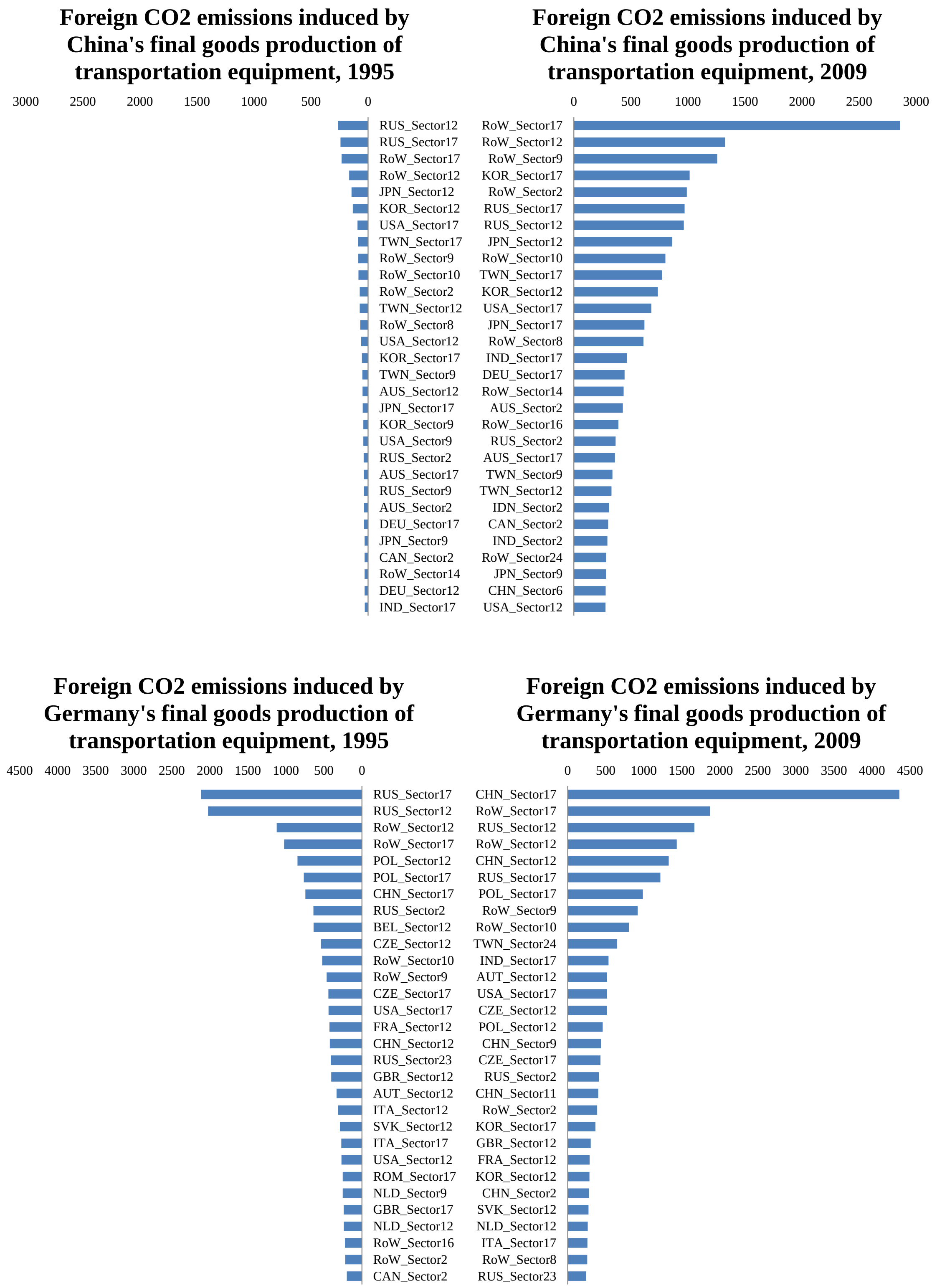


Figure B2 The potential environmental costs at the bilateral level for different energy sources (2009, kt/million US$)

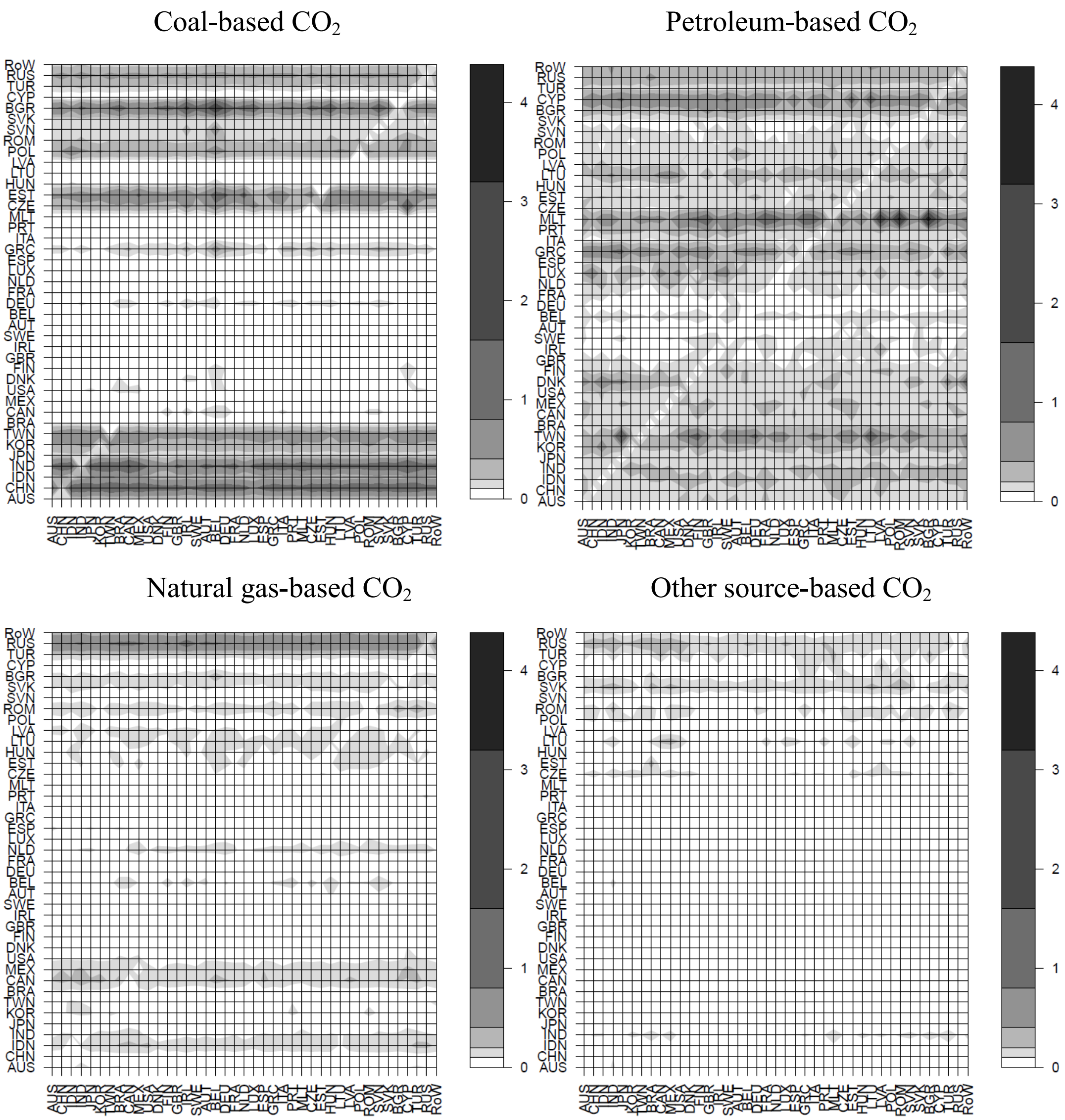


Figure B3 The US's trade balance of CO_2 emissions with selected partners by different GVC routes (2009, kt)

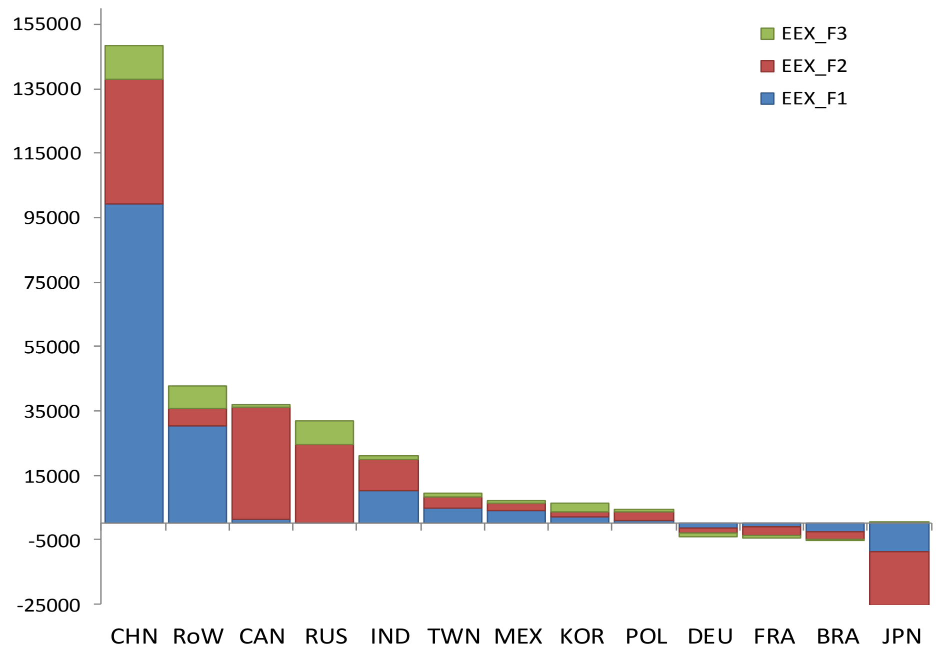
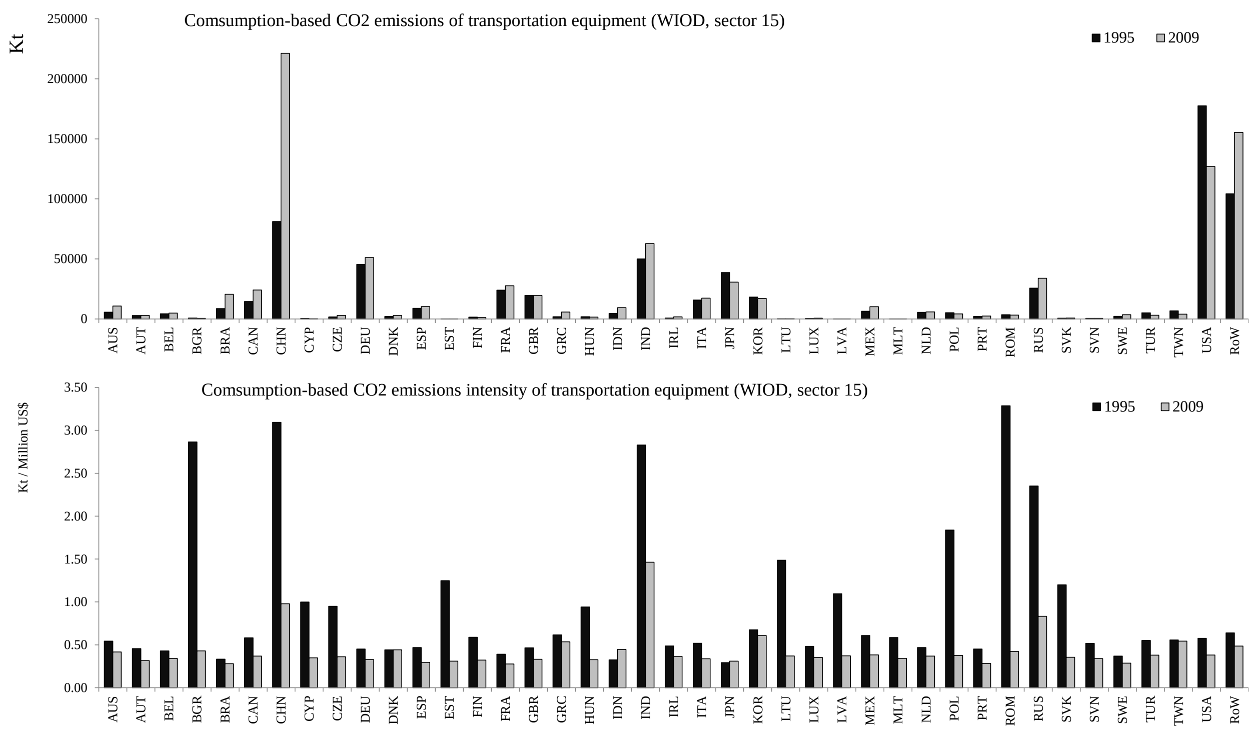


Figure B4 Consumption-based CO_2 emissions of a specific product (transportation equipment, WIOD sector 15 for 1995 and 2009)



Appendix C

WIOD country/region names

Code	Country Code	Name	EU 15	Annex B used
C1	AUS	Australia		✓
C2	AUT	Austria	✓	✓
C3	BEL	Belgium	✓	✓
C4	BGR	Bulgaria		✓
C5	BRA	Brazil		
C6	CAN	Canada		✓
C7	CHN	China		
C8	CYP	Cyprus		
C9	CZE	Czech Republic		✓
C10	DEU	Germany	✓	✓
C11	DNK	Denmark	✓	✓
C12	ESP	Spain	✓	✓
C13	EST	Estonia		✓
C14	FIN	Finland	✓	✓
C15	FRA	France	✓	✓
C16	GBR	United Kingdom	✓	✓
C17	GRC	Greece	✓	✓
C18	HUN	Hungary		✓
C19	IDN	Indonesia		
C20	IND	India		
C21	IRL	Ireland	✓	✓
C22	ITA	Italy	✓	✓
C23	JPN	Japan		✓
C24	KOR	South Korea		
C25	LTU	Lithuania		✓
C26	LUX	Luxembourg	✓	✓
C27	LVA	Latvia		✓
C28	MEX	Mexico		
C29	MLT	Malta		
C30	NLD	Netherlands	✓	✓
C31	POL	Poland		✓
C32	PRT	Portugal	✓	✓
C33	ROM	Romania		✓
C34	RUS	Russian Federation		✓
C35	SVK	Slovakia		✓
C36	SVN	Slovenia		✓
C37	SWE	Sweden	✓	✓
C38	TUR	Turkey		
C39	TWN	Taiwan		
C40	USA	United States		✓
C41	RoW	Rest of the World		

WIOD sector classification

Code	Description
S1	Agriculture, Hunting, Forestry and Fishing
S2	Mining and Quarrying
S3	Food, Beverages and Tobacco
S4	Textiles and Textile Products
S5	Leather, Leather and Footwear
S6	Wood and Products of Wood and Cork
S7	Pulp, Paper, Paper , Printing and Publishing
S8	Coke, Refined Petroleum and Nuclear Fuel
S9	Chemicals and Chemical Products
S10	Rubber and Plastics
S11	Other Non-Metallic Mineral
S12	Basic Metals and Fabricated Metal
S13	Machinery, Nec
S14	Electrical and Optical Equipment
S15	Transport Equipment
S16	Manufacturing, Nec; Recycling
S17	Electricity, Gas and Water Supply
S18	Construction
S19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
S20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
S21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
S22	Hotels and Restaurants
S23	Inland Transport
S24	Water Transport
S25	Air Transport
S26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
S27	Post and Telecommunications
S28	Financial Intermediation
S29	Real Estate Activities
S30	Renting of M&Eq and Other Business Activities
S31	Public Admin and Defence; Compulsory Social Security
S32	Education
S33	Health and Social Work
S34	Other Community, Social and Personal Services
S35	Private Households with Employed Persons

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