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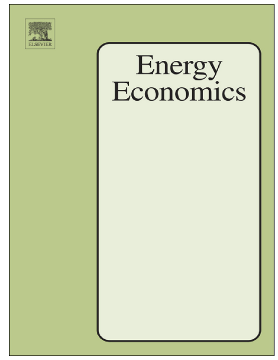

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The Global CO_2 Emission Cost of Geographic Shifts in International Sourcing

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Abstract: In this paper we simulated the global *direct* CO_2 emission cost of geographic shift of international sourcing for the period 1995–2011 by comparing the scenarios with and without geographic shift. Our simulations indicate that in 2011, had the share of trade by the sourcing economy remained at the level of 1995, 2000, 2005, and 2008 whereas the global final demand remained the same, global CO_2 emissions in production processes would have been 2.8 Gt, 2.0 Gt, 1.3 Gt, and 540 Mt, respectively, lower than the actual emissions. As there is a general outsourcing trend shifted from developed economies to developing economies, the overall direct emission costs have always been significantly positive. Further investigations by economy and industry show that such a geographic shift was mainly dominated by developed economies themselves and occurred in high-tech industries, such as production of Information and Communication Technology (ICT) goods and machinery, leading to positive emission cost in developing economies, especially China. Moreover, there is potentially even larger influence of geographic shift of sourcing on global CO_2 emissions, as such a shift would stimulate the economic growth and consumptions in developing economies, consequently this may bring additional energy demand and CO_2 emissions. Our results addressed the urgency of eliminating in carbon emission intensity gap between developing and developed economies and the successful development of new, scalable low carbon energy sourcing and technologies across the world.

Keywords: Geographic Shift; International Sourcing; Emission cost; Global CO_2 emissions

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Competing financial interests

The authors declare no competing financial interests.

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1. Introduction

The last few decades have witnessed fluctuating growth in international trade, with a strong boom from US$ 5.17 trillion in merchandise exports in 1995 to US$ 16.16 trillion in 2008, a sharp fall due to the financial crisis in 2009, and then a moderate recovery from US$ 15.30 trillion in 2010 to US$ 19.00 trillion in 2014 (WTO, 2015). Except for the period of 2008–2009, world merchandise exports have grown at a much higher rate than world gross domestic product (GDP) in recent decades (WTO, 2015).

Meanwhile, the pattern of world trade is also gradually changing. Lower trade cost and improved communication technology have fostered an increase in the internationalization of production, for which the means of production are increasingly unbundled into different stages that are conducted in different economies/regions (Baldwin, 2011; Timmer et al., 2014; Draper, 2013). As a result, the growth of trade in the past decades has been characterized by a growth in intermediates trade (Hummels et al., 2001; Sturgeon and Gereffi, 2009; De Backer and Yamano, 2012;), accompanied by a geographic shift of source regions (OECD, WTO and WB, 2014; AfDB, OECD and UNDP, 2014; WTO, 2015). The share of developing economies' exports in world totals increased from 26% in 1995 to 44% in 2014, while the share of developed economies' exports decreased correspondingly by 18 percentages (WTO, 2015). As Lehmann (2012) summarized, the center of global production and trade originated with the industrial revolution in Britain; after which it shifted to Western Europe (especially Germany); then, to the U.S.; and, two decades after World War II, to Japan; Asia's Four Tigers (especially South Korea and Taiwan); China; and now, started to move further to less developing economies in South Asia and Africa (see also, Stratfor, 2013; AfDB, OECD and UNDP, 2014).

In parallel with this boom in world trade, there has been a rapid growth in global greenhouse gas (GHG) emissions. Global CO_2 emissions have accelerated from 21.84 gigatonnes (Gt) in 1995 to 29.47 Gt in 2008, after which occurred a slight slowdown to 28.97 Gt in 2009 and then a rebound to 32.30 Gt in 2014 (IEA, 2015). The international trade brought a separation of consumptions and productions, and consequently carbon leakage (see, e.g. Wiedmann et al., 2007; Peters and Hertwich, 2008; Davis and Caldeira, 2010; Peters, 2010; Peters et al., 2011; Feng et al., 2013). Following this line, some literatures have tried to provide evidence on the pollution haven hypothesis (PHH), that argues international trade contributes to an increase in global GHG emissions, as companies locate production activities in countries with comparatively lax environmental regulation and high emission intensities (Copeland and Taylor, 2004). Assuming that each region is capable of producing the goods they import, they calculate a net balance of avoided emissions and evaluate whether such trade increases or reduces emissions. Many of the works have focused their interest in China, and found that trade with China in developed countries has led to an increase in global emissions, confirming the pollution haven hypothesis (see, e.g., Zhang, 2012; López et al., 2013; Liu et al., 2016a and 2016b).

Another stream of literatures adopted the structural decomposition analysis (SDA) to investigate the changing structure of international trade on global CO_2 emissions growth, and generally found net positive effects (see, e.g. Arto and Dietzenbacher, 2014; Hoekstra et al., 2016; Malik and Lan, 2016). By decomposing the global GHG emissions, Arto and Dietzenbacher (2014), for example, have found that the changes in the structure of international trade increased global GHG emissions by 0.58 Gt CO_2 equivalents in the period 1995–2008. In a similar vein, Hoekstra et al. (2016) decomposed the effects of changes in the structure of international trade between different income groups of economies on their CO_2 emissions growth. Referring to the sum of these effects as the emission cost of international sourcing, they found the net global effects derived from the change of international sourcing pattern amounts to 18% of the total global CO_2 emissions growth (i.e. 1.1 Gt) over the period 1995–2007. Defining the outsourcing as imports of carbon emissions embodied commodities, Malik and Lan (2016) also discussed the changes of outsourcing trends and decomposed their contributions on global CO_2 emissions growth by region and commodity over the period 1990–2010.

In this paper, we adopt Hoekstra et al.'s (2016) idea, referring to the structure of international trade as the "international sourcing," and plan to discuss the emission cost of the geographic shift of international sourcing from a new what-if aspect. As aforementioned, the developing economies account for an increasing share of global exports. The geographic shift of international sourcing can therefore be identified as a change of the purchases of intermediate and final goods from new source economies (very possibly developing economies) rather than from previous trading partners (possibly developed economies) or domestic production. Given the gap in energy efficiency and fuel mix between developing and developed economies, such geographic shift from developed economies (with higher energy efficiencies and somewhat greater reliance on clean energies) to developing economies (with lower energy efficiencies and much greater reliance on fossil fuels) would lead to additional global CO_2 emissions at the aggregate level. In our paper, this situation is referred as emission cost of geographic shift in international sourcing (ECGS).

Unlike the studies that rely on SDA to isolate the effects of a changing trade pattern on global emissions growth (see, e.g. Arto and Dietzenbacher, 2014; Hoekstra et al., 2016; Malik and Lan, 2016), in this paper we adopted a what-if scenario analysis approach to quantify the *direct* emission cost of the geographic shift of international sourcing. The idea is to simulate the extent to which global emissions would have been lower when assuming the global demand for goods remained the same in the absence of the geographic shift to developing economies. More specifically, for a specific year *t1*, we simulate the global CO_2 emissions assuming that the structure of international trade by sourcing country/region is replaced by the structure in year *t0*, and then compare the results with the actual global CO_2 emissions as a means of quantifying the emission cost of geographic shift in international sourcing for year *t1*. This would help to provide another aspect on the role of international trade on global CO_2 emissions growth.

Recent years have seen a proliferation of global multi-regional input–output tables (GMRIO) that are available to analyze the global value chains and emissions issues, such as Eora, EXIOBASE, OECD-ICIO, and GTAP-MRIO (see Tukker and Dietzenbacher (2013) for an explicit review). To conduct the empirical analysis, this paper employed the inter-country input–output tables (ICIO) complied by the Organisation for Economic Co-operation and Development (abbr. as OECD) (OECD, 2014). One of the unique features of the OECD-ICIO is that it distinguishes processing exports and normal productions for China and Mexico. It has been widely acknowledged that the production recipes and emission intensity of processing exports and normal productions is highly different; as a result, a distinction of their activities in IO tables is necessary (see, e.g. Dietzenbacher et al., 2012; Su et al., 2013; Jiang et al., 2015 and 2016). Employing OECD-ICIO, our paper is also different from the studies that use other GMRIO databases by distinguishing the production chains of processing exports with normal production in China and Mexico.

The paper is organized as follows. In section 2, we introduce our methods and data sources; in section 3, we present and discuss our results of emission cost of the geographic shift of international sourcing, at both the aggregate and individual region/industry level. Some policy-related implications of our findings are provided in section 4.

2. **Methodology and Data**

2.1. Global Multi-Regional Input–Output (GMRIO) framework and data source

The GMRIO has been widely accepted in tracing the CO_2 emissions footprint along global production chains (see Wiedmann (2009) and Minx et al. (2010) for reviews). Table 1 presents the GMRIO framework employed in this paper. The diagonal matrices of intermediate use give the intra-regional intermediate deliveries, that is, the elements z_{ij}^{rr} of matrix $\mathbf{Z}^{\mathrm{rr}}$ give the intermediate deliveries from industry *i* in region *r* to industry *j* in region *r*, with *i*, *j* =1,…,*m*, where *m* is the number of industries, and *r* =1,…,*n*, where *n* is the number of regions. The non-diagonal matrices indicate inter-regional intermediate deliveries, that is, the elements z_{ij}^{rs} of matrix $\mathbf{Z}^{\mathrm{rs}}$ indicate the deliveries of products from industry *i* (=1,..,m) in region *r* (=1,..,n) for input use in industry *j* (=1,..,m) in region *s* (=1,..,n; ≠ *r*). The matrices of final demand $\mathbf{F}^{\mathrm{rs}}$(*r*, *s*=1,...,n) are divided into consumption $\mathbf{F}_{\mathrm{cons}}^{\mathrm{rs}}$ (*r*, *s*=1,...,n) (including consumption by households, governments, and non-government organizations), and investment $\mathbf{F}_{\mathrm{inv}}^{\mathrm{rs}}$ (*r*, =1,...,n) (i.e. fixed capital formation). $\mathbf{X}^{\mathrm{r}}$ (*r* =1,...,n) represents the total output in region *r* (=1,..,n).

Table 1. The multi-regional input-output framework

			Intermediate Use			Final Use					Total Output
			Region 1	…	Region n	Region 1		…	Region n		
			Industry 1,.., m		Industry 1,…,m	Cons.	Inv.		Cons.	Inv.	
Intermediate Use	Region 1	industry	Z^{11}	…	Z^{1n}	F_{cons}^{11}	F_{inv}^{11}	…	F_{cons}^{1n}	F_{inv}^{1n}	X^{1}
	…	…	…	…	…	…	…	…	…	…	…
	Region n	industry	Z^{n1}	…	Z^{nn}	F_{cons}^{n1}	F_{inv}^{n1}	…	F_{cons}^{nn}	F_{inv}^{nn}	X^{n}
Value Added			V^{1}	…	V^{n}						
Total Inputs			X^{1}	…	X^{n}						

According to Table 1, we have row equilibrium in matrix notation as follows:

$$\begin{bmatrix} \mathbf{Z}^{11} & \cdots & \mathbf{Z}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{Z}^{n1} & \cdots & \mathbf{Z}^{nn} \end{bmatrix} + \begin{bmatrix} \mathbf{F}^{11} + \cdots + \mathbf{F}^{1n} \\ \cdots \\ \mathbf{F}^{n1} + \cdots + \mathbf{F}^{nn} \end{bmatrix} = \begin{bmatrix} \mathbf{X}^{1} \\ \vdots \\ \mathbf{X}^{n} \end{bmatrix} \quad (1)$$

The direct input coefficients can then be obtained by normalizing the columns in the IO table; that is:

$$\mathbf{A}^{\mathrm{rs}} = \mathbf{Z}^{\mathrm{rs}}(\widehat{\mathbf{X}^{\mathrm{s}}})^{-1} \tag{2}$$

The Leontief inverse is thus defined as $\mathbf{B} = \begin{bmatrix} \mathbf{B}^{11} & \cdots & \mathbf{B}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{n1} & \cdots & \mathbf{B}^{nn} \end{bmatrix} = (\mathbf{I} - \mathbf{A})^{-1} = \begin{bmatrix} \mathbf{I} - \mathbf{A}^{11} & \cdots & -\mathbf{A}^{1n} \\ \vdots & \ddots & \vdots \\ -\mathbf{A}^{n1} & \cdots & \mathbf{I} - \mathbf{A}^{nn} \end{bmatrix}^{-1}$. Using $\mathbf{E}^{\mathrm{r}}_{\mathrm{carbon}}$ to denote the matrix of production-based CO_2 emissions by sector in region *r*, we would have the matrix of carbon emissions intensity per unit of output by sector in region *r* as:

$$\mathbf{CA}^{\mathrm{r}} = \mathbf{E}^{\mathrm{r}}_{\mathrm{carbon}}(\widehat{\mathbf{X}^{\mathrm{r}}})^{-1} \tag{3}$$

The CO_2 emissions generated along global production chains can be traced as follows:

$$\begin{bmatrix} \mathbf{E}^{11} & \cdots & \mathbf{E}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{E}^{n1} & \cdots & \mathbf{E}^{nn} \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{CA}}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{CA}}^{n} \end{bmatrix} \begin{bmatrix} \mathbf{B}^{11} & \cdots & \mathbf{B}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{n1} & \cdots & \mathbf{B}^{nn} \end{bmatrix} \begin{bmatrix} \mathbf{F}^{11} & \cdots & \mathbf{F}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{F}^{n1} & \cdots & \mathbf{F}^{nn} \end{bmatrix} \tag{4}$$

where the elements E_{io}^{rs} of matrix $\mathbf{E}^{\mathrm{rs}}$ indicate the production-based emissions of industry *i* (=1,..,m) in region *r* (=1,..,n) led by the final demand in region *s* (=1,..,n). The summation of $\mathbf{E}^{\mathrm{rs}}$, $\sum_s \mathbf{E}^{\mathrm{rs}}$ and $\sum_{\mathrm{r}} \mathbf{E}^{\mathrm{rs}}$ will give the production-based emissions of region *r* and consumption-based emissions of region *s*, respectively.

As mentioned, our GMRIO database is an inter-country input-output database compiled by OECD. This is a symmetric industry-by-industry input-output database. It covers 62 regions (34 OECD regions and 28 non-OECD regions) and 34 industries, and years 1995, 2000, 2005, 2008, 2009, 2010, and 2011. In particular, it distinguishes the production of Mexico into global manufacturing (mainly serving as processing production) and non-global manufacturing (serving as domestic production), and that of China into domestic demand, processing exports, and normal exports. Therefore, we would have n=65 and m=34 for the intermediate deliveries, and $\mathbf{E}^{\mathrm{r}}_{\mathrm{carbon}}$ and $\mathbf{CA}^{\mathrm{r}}$ (*r* =1,...,65) as a 1*34 vector, $\mathbf{A}^{\mathrm{rs}}$ and $\mathbf{B}^{\mathrm{rs}}$ (*r,s* =1,..,65) as 34*34 matrix, **A** and **B** as 2210*2210 matrix. For the final use, after we aggregate the consumptions and investment, $\mathbf{F}^{\mathrm{rs}}$ (*r* =1,..,65; *s* = 1,...,62) is a 34*1 vector and **F** is a 2210*62 matrix. Unlike the other GMRIO database, the OECD-ICIO are only released in current prices. To convert them into constant prices for our SDA study of the period t0-t1, we followed Lan et al.'s (2016) procedure, i.e. the "convert-first then deflate" procedure (see also Fremdling et al. 2007). That is, after converting the monetary data for each country into U.S. dollars, we used the double-deflation method with sectoral Producer Price Indexes for the US economy and deflated the GMRIO table at year *t1* from current price into a constant price of year *t0*[1].

Regarding CO_2 emissions, we mainly rely on IEA's statistics on CO_2 emissions from fuel combustion and reconcile them into the classification of OECD-ICIO table (IEA, 2014).[2] With respect to the CO_2 emissions by production type for China and Mexico, we adopted the method of Jiang *et al.* (2016) to use intermediate energy in an input-output table to proportionally decompose

[1] Please refer to appendix A of Lan et al. (2016) for the detailed deflation procedure and the explanations.
[2] That means, in this paper we only focus on the CO_2 emissions generated in the productions of goods and services. The CO_2 emissions from land use, forestry, and household activities by combustions of fossil fuels (e.g. driving cars or cooking) are excluded.

the CO_2 emissions of China (and Mexico) by three (and two) production types. China's (and Mexico's) disaggregations by production type are calibrated to ensure that a re-aggregation would result in an official release of IEA.

2.2. The emission cost of geographic shift in international sourcing (ECGS)

The shift of international sourcing geography not only influences worldwide input structures of trade in intermediate products, but also influences final demand patterns through trade in final products. The simulations used to capture the impact of shifting geography on global emissions were carried out by assuming the structure of international trade by sourcing in year *t1* would be reverted to the structure in year *t0*.

Our first step is therefore to isolate the change in the structure of international trade, i.e., the pattern of international sourcing. In this paper, we follow the line with Xu and Dietzenbacher (2014), Arto and Dietzenbacher (2014), and Hoekstra et al. (2016), and decompose the **A**-matrix into technical coefficients and pattern of international sourcing. That is, define a stacked matrix $\mathbf{A}^* = \begin{bmatrix} \mathbf{A}^{*1} & \cdots & \mathbf{A}^{*n} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{*1} & \cdots & \mathbf{A}^{*n} \end{bmatrix}$ with $\mathbf{A}^{*s}$ represents the technical intermediate input coefficients matrix of region s irrespective of the sourcing region, and $\mathbf{C} = \begin{bmatrix} \mathbf{C}^{11} & \cdots & \mathbf{C}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{C}^{n1} & \cdots & \mathbf{C}^{nn} \end{bmatrix}$ with $\mathbf{C}^{rs}$ indicates the share sourced from region *r* (=1,...,65) in the intermediate inputs of region *s*, and $\mathbf{C}^{S} = \begin{bmatrix} 0 & \cdots & \mathbf{C}^{1s} & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & & \mathbf{C}^{ss} & & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{C}^{65,s} & \cdots & 0 \end{bmatrix}$ indicates the source pattern of region s, then the A-matrix can be decomposed as

$$\mathbf{A} = \mathbf{C} \otimes \mathbf{A}^* = (\textstyle\sum_s \mathbf{C}^{S}) \otimes \mathbf{A}^* \quad (5)$$

where $\otimes$ stands for the Hadamard product.

Similarly, the final demand can be decomposed as

$$\mathbf{F} = [\textstyle\sum_s \mathbf{F}^{S}] \otimes \mathbf{Y}^* \quad (6)$$

Where $\mathbf{Y}^*$ represents the stacked final demand and $\mathbf{F}^{S}$ represents the sourcing pattern of final demand. Then let subscript t1 denote the year *t1*, actual emission (Scenario I) can be calculated as:

$$\begin{bmatrix} \mathbf{E}_{t1}^{11} & \cdots & \mathbf{E}_{t1}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{E}_{t1}^{n1} & \cdots & \mathbf{E}_{t1}^{nn} \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{CA}}_{t1}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{CA}}_{t1}^{n} \end{bmatrix} \cdot [\mathbf{I} - (\textstyle\sum_s \mathbf{C}_{t1}^{s}) \otimes \mathbf{A}_{t1}^{*}]^{-1} \cdot (\textstyle\sum_s \mathbf{F}_{t1}^{s}) \otimes \mathbf{Y}_{t1}^{*} \quad (7)$$

Scenario II assumes that the global final demands $\mathbf{Y}^*$, production technique $\mathbf{A}^*$ and emission intensity $\mathbf{CA}^r$ (r =1,...,65) remain unchanged, and the structure of international trade by sourcing region is replaced by those structures in year *t0*, then the production-based CO_2 emissions in Scenario II can be calculated as:

$$\begin{bmatrix} \mathbf{E}_{t1}^{11}\_II & \cdots & \mathbf{E}_{t1}^{1n}\_II \\ \vdots & \ddots & \vdots \\ \mathbf{E}_{t1}^{n1}\_II & \cdots & \mathbf{E}_{t1}^{nn}\_II \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{CA}}_{t1}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{CA}}_{t1}^{n} \end{bmatrix} \cdot [\mathbf{I} - (\sum_s \mathbf{C}_{t0}^s) \otimes \mathbf{A}_{t1}^*]^{-1} \cdot (\sum_s \mathbf{F}_{t0}^s) \otimes \mathbf{Y}_{t1}^* \quad (8)$$

The emission cost in region *r* and year *t1* due to the geographic shift of international sourcing for the period t0-t1 would be:

$$ECGS_{t1}^{r}\_II = \sum_s E_{t1}^{rs} - \sum_s E_{t1}^{rs}\_II \quad (9)$$

where $ECGS_{t1}^{r}\_II > 0$ suggests that the world is inclined to purchase more intermediate or/and final products from region *r* (directly and indirectly), and vice versa. To sum up, the $ECS_{t1}^{r}\_II$ over region *r* (=1,...,65) would give the global emission cost due to the geographic shift of international sourcing for the period t0-t1. At the aggregate level, $ECGS_{t1\_}II = \sum_r ECGS_{t1}^{r}\_II > 0$ suggests that the world is inclined to purchase more intermediate or/and final products from economies with higher emission intensities (mostly developing economies). For example, China has highly relied on coal as its primary energy input, and as a result its CO_2 emission intensity per US\$ GDP in constant price has been around 1.8–2.0 times that of the world average (IEA, 2014). When China's exports account for more of the share of the world total, that is, the world is inclined to purchase more products (incl. intermediate and final products) from China rather than from the economies with lower emission intensities, there are additional CO_2 emissions, called the emission cost of the geographic shift in international sourcing (i.e. ECGS) in this paper.

Similarly, the emission cost can also be traced by the source region (Scenario III and IV for intermediate and final products respectively) and industry (Scenario IV), please refer to appendix A for more detail.

As aforementioned, our method has a different aspect compared with the structural decomposition method, such as Arto and Dietzenbacher (2014), and Hoekstra et al. (2016) employed, when isolating the impact of a changing trade pattern on global emissions. To clarify our contribution, we use a two-country model with one product to describe the difference between our method and that of SDA[3].

Assume China is country A and the developed world is country B. Use e_A^t and e_B^t to represent the emission intensity of country A and B in year *t*, s_A^t and s_B^t to represent the share of country A and B in world production in year *t*, and y^t to represent the world's total production/demand. The changing trade pattern could be reflected by the change of s_A^t and s_B^t, and we always have $s_A^t + s_B^t = 1$ for any specific year *t*.

For the period t0-t1, the SDA method in polar forms used by investigators such as Arto and Dietzenbacher (2014) and Hoekstra et al. (2016) would decompose global emissions growth from

[3] See Lenzen (2016) for a recent review of SDA applications in energy use and carbon emissions under GMRIO framework.

year *t0* to *t1* as:

$$\Delta E = e_A^{t1} \cdot s_A^{t1} \cdot y^{t1} + e_B^{t1} \cdot s_B^{t1} \cdot y^{t1} - (e_A^{t0} \cdot s_A^{t0} \cdot y^{t0} + e_B^{t0} \cdot s_B^{t0} \cdot y^{t0}) \tag{10}$$

$$= \tfrac{1}{2}[(e_A^{t1} - e_A^{t0}) \cdot s_A^{t1} \cdot y^{t1} + (e_A^{t1} - e_A^{t0}) \cdot s_A^{t0} \cdot y^{t0} + (e_B^{t1} - e_B^{t0}) \cdot s_B^{t1} \cdot y^{t1} + (e_B^{t1} - e_B^{t0}) \cdot s_B^{t0} \cdot y^{t0}]$$

$$+\tfrac{1}{2}[e_A^{t1} \cdot (s_A^{t1} - s_A^{t0}) \cdot y^{t0} + e_A^{t0} \cdot (s_A^{t1} - s_A^{t0}) \cdot y^{t1} + e_B^{t1} \cdot (s_B^{t1} - s_B^{t0}) \cdot y^{t0} + e_B^{t0} \cdot (s_B^{t1} - s_B^{t0}) \cdot y^{t1}]$$

$$+\tfrac{1}{2}[e_A^{t1} \cdot s_A^{t1} \cdot (y^{t1} - y^{t0}) + e_A^{t0} \cdot s_A^{t0} \cdot (y^{t1} - y^{t0}) + e_B^{t1} \cdot s_B^{t1} \cdot (y^{t1} - y^{t0}) + e_B^{t0} \cdot s_B^{t0} \cdot (y^{t1} - y^{t0})]$$

where the second term gives the contributions of changing trade pattern. Given $s_A^t + s_B^t = 1$, we would have the impact of changing trade pattern on global emissions growth as:

$$E_{\Delta S} = \tfrac{1}{2}[(e_A^{t1} - e_B^{t1}) \cdot \Delta S_A \cdot y^{t0} + (e_A^{t0} - e_B^{t0}) \cdot \Delta S_A \cdot y^{t1}] \tag{11}$$

In contrast, our paper quantified the global emission cost due to the changing trade pattern as:

$$ECGS_{t1} = e_A^{t1}(s_A^{t1} - s_A^{t0})y^{t1} + e_B^{t1}(s_B^{t1} - s_B^{t0})y^{t1} = (e_A^{t1} - e_B^{t1}) \cdot \Delta S_A \cdot y^{t1} \tag{12}$$

The two methods give very relevant (as both are related to e_A^t, e_B^t, ΔS, etc.) but different results. Where SDA method addresses the temporal change with consideration of both change in trade share and trade volumes, for which the changing trading shares are weighted by total final production/demand for both year *t0* and *t1*; our method only concerns the change of trade shares, for which the changing trading shares are weighted only by total final production/demand in year *t1*.

Meanwhile, our measurement is also different with the PHH-relating measurement. In the literatures of PHH, the role of trade on global emissions is normally analyzed using the balance of avoided emissions (BAE) that is measured by the difference between the emissions embodied in exports and the emissions avoided by imports into two countries (López et al., 2013, Zhang et al., 2017; López et al., 2017). Following the above example of country A (China) and country B (developed countries), let $y_{ls}^t(l, s = A, B)$ indicate the final demand of country *s* (=A, B) provided by country *l* (=A, B), we would have the BAE of country A to which it trades with country B in year *t1* is:

$$BAE_{AB}^{t1} = e_A^{t1} y_{AB}^{t1} - e_A^{t1} y_{BA}^{t1} \tag{13}$$

The sign of this expression is eq.13 influenced by the sign, positive or negative, of the trade balance. Therefore, the net effect of the trade would be measured by the net NBAE as:

$$NBAE = BAE_{AB}^{t1} + BAE_{BA}^{t1} = e_A^{t1} y_{AB}^{t1} - e_A^{t1} y_{BA}^{t1} + e_B^{t1} y_{BA}^{t1} - e_B^{t1} y_{AB}^{t1}$$

$$= (e_A^{t1} - e_B^{t1}) y_{AB}^{t1} - (e_A^{t1} - e_B^{t1}) y_{BA}^{t1} \tag{14}$$

If we compare eq. 14 with eq. 12, we could find some similarities and differences into the global emissions cost and the pollution haven hypothesis. PHH concerns to the spatial difference of emission intensity in year *t1*, and the trade flows among country A and country B in year *t*1. Our emission cost measurement however concerns spatial difference of emission intensity in year *t*1 as well as the changing trade pattern from *t*0 to *t*1.

3. Results

3.1. The global emissions cost of geographic shift in international sourcing, 1995–2011

In figure 1 we first compare the "actual" global CO_2 emissions (our Scenario I is measured by eq. 7) with an alternative Scenario II (measured by eq. 8) for the period 1995–2011. The alternative Scenario II assumes that the pattern of international sourcing, i.e., structure of international trade for both intermediate and final products, was replaced by the pattern in one specific previous year while the others remained unchanged. For example, the brown line indicated as "1995 structure" gives the simulated emissions for 2000–2011 when the structure of trade remained as it did in 1995, and the world final demand remained as it did in 2000–2011. The difference between Scenario I and Scenario II (with a structure for different years) is the so-called emission cost of the geographic shift in international sourcing (ECGS).

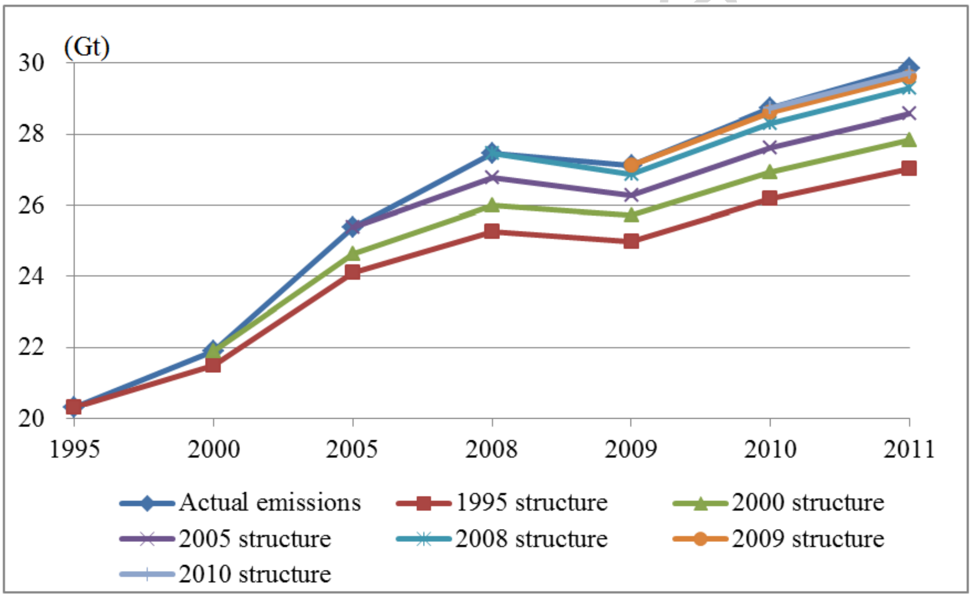


Figure 1. The global emissions with and without geographic shift of international sourcing (Scenario I and II, assuming structures of international trade in different years are adopted)

Figure 1 indicates that the global emissions would be reduced if the structure of trade in the previous years was adopted. This is not surprising, given the facts that the share of developing economies' exports in world trade has significantly increased (WTO, 2015), and the average emission intensity of OECD economies is around 38–41% lower than that of non-OECD economies (IEA, 2014). Specifically, our simulations indicate that, in 2011, had the structure of trade remained in the level of 1995, global CO_2 emissions in production processes would have been 27.04 Gt rather than the "actual" (Scenario I) level of 29.85 Gt.[4] In other words, the ECGS

[4] In this paper we only focused on the CO_2 emissions generated in production process of goods and services, and excluding the emissions by household activities,

toward developing economies increased the annual global CO_2 emissions, in 2011, by 2.81 Gt from 1995 to 2011. If the structure of trade in recent years, 2000, 2005, 2008, etc., was adopted, the emissions cost is still positive, but the amount would become smaller. For example, if the trade structure of 2010 was adopted, the global CO_2 emissions in 2011 would have been 29.74 Gt, lower than the actual emissions by 110 Mt.

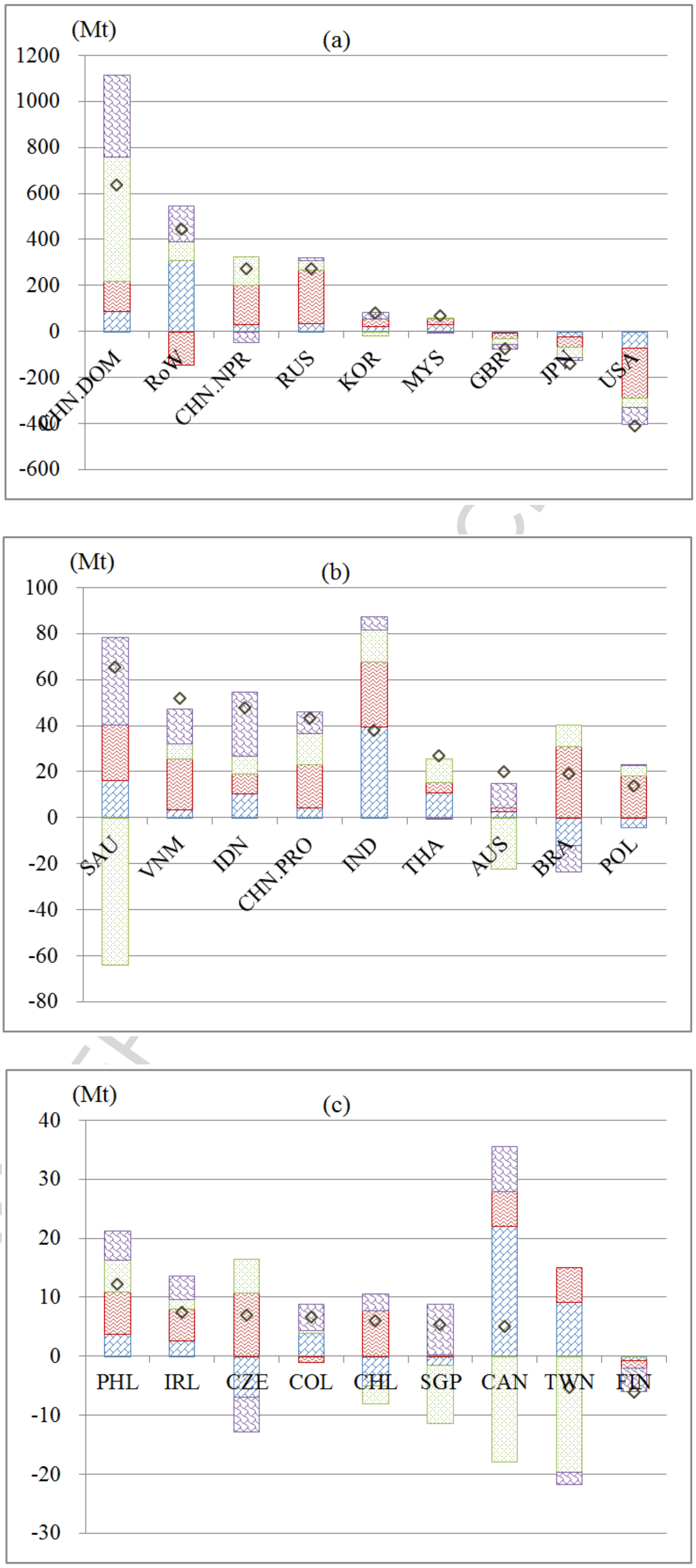
Our simulations of ECGS are larger than the studies using the SDA method isolating the effect of changing pattern of international sourcing. For example, Arto and Dietzenbacher (2014) identified that the changes in the structure of international trade increased global GHG emissions by 0.58 Gt CO_2 equivalent in the period 1995–2008; Hoekstra et al. (2016) found that the net global effects of changing source were up to 1.1 Gt over the period 1995–2007. For the period 1995–2008, our simulations indicate that if the trade structure of 1995 were adopted, the global CO_2 emissions in 2008 would have been 25.25 Gt, lowering the actual emissions by 2.23 Gt. Recalling the comparisons of formulas between our method and SDA (eq. 12 vs. eq. 11), the difference is generated from

$$ECGS_{t1} - E_{\Delta S} = \frac{1}{2}(e_A^{t1} - e_B^{t1}) \cdot \Delta S_A \cdot (y^{t1} - y^{t0}) + \frac{1}{2}[(e_A^{t1} - e_B^{t1}) - (e_A^{t0} - e_B^{t0})] \cdot \Delta S_A \cdot y^{t1} \quad (15)$$

As aforementioned, the emission intensity gap among OECD and non-OECD economies remains at a relatively stable level for the period 1995–2011. This implies that the latter part $\frac{1}{2}[(e_A^{t1} - e_B^{t1}) - (e_A^{t0} - e_B^{t0})] \cdot \Delta S_A \cdot y^{t1}$ is close to zero. The difference between our results and the SDA method is thus determined by the former part $\frac{1}{2}(e_A^{t1} - e_B^{t1}) \cdot \Delta S_A \cdot (y^{t1} - y^{t0})$. Given the significant increase of global final demand, and stable (positive) emission intensity gap between OECD and non-OECD countries, it is not surprising that our results are much higher than that of SDA method.

3.2. The regional emissions cost of geographic shift in international sourcing, 1995–2011

If we further divide the entire period 1995–2011 into four intervals, that is, 1995–2000, 2000–2005, 2005–2008, and 2008–2011, the emission increase due to the geographic shift of sourcing (ECGS) is 416 Mt, 768 Mt, 707 Mt, and 540 Mt, respectively (Fig. 1). The ECGS grows especially during 2000–2008. In figure 2 we present the national emission cost due to the geographic shift of the global sourcing pattern, i.e., the structure of global inter-country trade for the four intervals, and the total emission cost for the entire period 1995–2011 as measured by $ECGS_{t1}^{r}\_II$ in eq. 10 for each region *r*. Positive cost suggested that the economy is increasingly involved in the international sourcing of carbon-intensive products (including intermediate and final products) over the period. Negative cost suggested that the economy was involved in the international sourcing to a lesser extent over the period and/or the offshoring process go to countries with less emissions intensities. Note that the total cost for the period 1995–2011 does not necessarily equal the sum of the emissions cost of the four sub-intervals. To simplify the study, we only list the economies with total cost larger than 5 Mt for 1995-2011.


(Mt)
(a)
1200
1000
800
600
400
200
0
-200
-400
-600
CHN.DOM
RoW
CHN.NPR
RUS
KOR
MYS
GBR
JPN
USA
(Mt)
(b)
100
80
60
40
20
0
-20
-40
-60
-80
SAU
VNM
IDN
CHN.PRO
IND
THA
AUS
BRA
POL
(Mt)
(c)
40
30
20
10
0
-10
-20
-30
PHL
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SGP
CAN
TWN
FIN

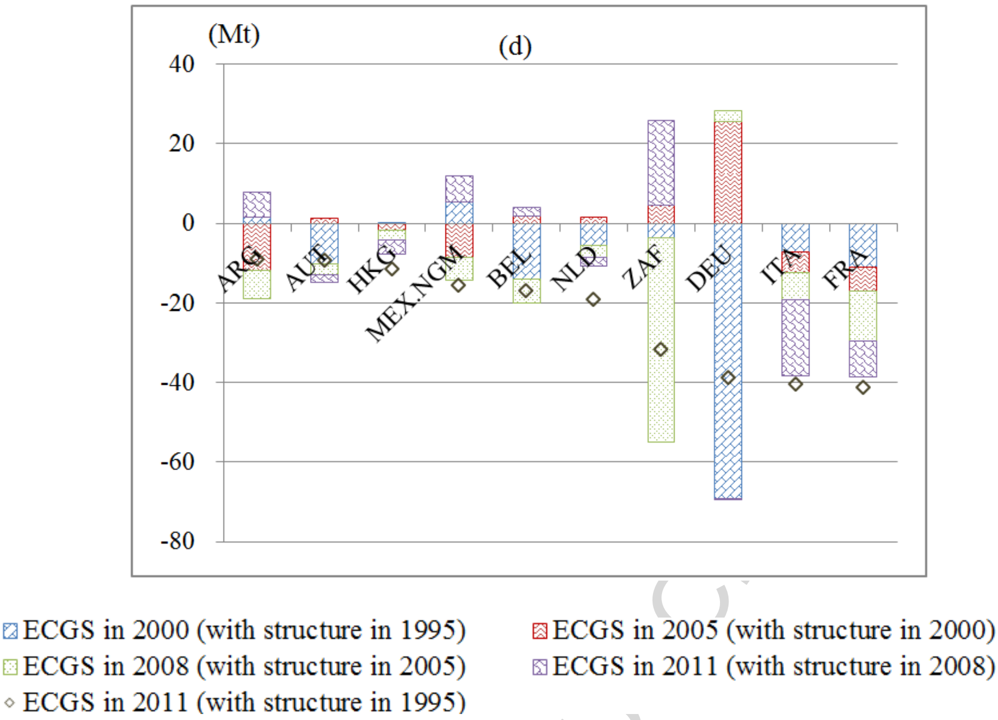


Figure 2. The regional emissions cost of geographic shift in international sourcing (ECGS), 1995–2011. Refer to appendix table B for the abbreviation of region.

During 1995–2011, the USA shrunk its share of international sourcing the most, followed by Japan and the UK. Emissions from the USA, Japan, and the UK in 2011, assuming the structure of international outsourcing was as same as that in 1995, would have been respectively 411 Mt, 141 Mt, and 78 Mt larger. These economies reduce their share in the international sourcing, especially for carbon-intensive products. In contrast, China expanded its share in international sourcing the most for the same period 1995–2011; it is followed by Russia and South Korea. Without the increase of involvement in the international sourcing, China's emissions would have been 953 Mt lower in 2011. The emission costs of Russia and South Korea were also very large, at 273 Mt and 77 Mt, respectively.

In general, most developed economies shrunk their shares in international sourcing, such as most EU15 economies, showing a negative emissions cost from 1995 to 2011. There are also exceptions, such as Australia and Canada; these so-called resource-rich developed economies show strong involvement in sourcing by exporting raw materials and resources, and therefore show positive emissions cost (see also Malik and Lan, 2016). In contrast, most developing economies expanded their shares in international sourcing, showing positive emissions cost. Among them, Southeast Asia (e.g., Malaysia, Vietnam, Indonesia, Thailand, and the Philippines), Latin America (e.g., Brazil, Columbia, and Chile), Eastern European economies (e.g., Poland, Czech Republic, and Estonia), and Saudi Arabia have relatively strong performance, with the emission costs larger than 5 Mt for the period 1995–2011. There are also several developing countries showing a negative emission cost in different years, although insufficient to generate a net saving of emissions throughout the period, such as Brazil from 2008 to 2011, Chile from 1995 to 2000, South Africa from 2005 to 2008, and Argentina from 2000 to 2008. These savings are consistent with the absence of pollution haven hypothesis or net savings generated through international trade generated by resource-intensive countries as they are more efficient in the extraction and processing than the countries supplied by (see also, Zhang et al., 2017; López et al., 2017).

Note that there are also significant temporal changes across the four sub-periods. After gaining entry into the World Trade Organization (WTO), China has largely expanded its share in international sourcing, even after the international financial crisis in 2008. This is reflected as a positive and growing ECGS of China for all sub-periods. By production type, the non-processing exports of China had expanded significantly in 2000–2008 (with ECGS at 297 Mt), and then shrunk in the post-crisis era in 2008–2011 (with ECGS at –47 Mt), while the domestic productions of China have continuously expanded its market share ever since 2005 (with ECGS at 542 Mt and 353 Mt in 2005–2008 and 2006–2011, respectively) as per capita income level increases. To a lesser extent, Southeast Asian economies, such as Malaysia, Vietnam, Indonesia, Thailand, and the Philippines, also continuously expanded their share in international sourcing in 1995–2011, showing positive emission costs in all four sub-periods. Latin America and Eastern European developing economies mainly experienced expansions of sourcing in 2000–2008, while after the crisis they experienced drops, showing ECGS turning to negative in 2008–2011. Clearly China still outperformed the South Asian and Latin American economies in terms of recession as a recipient of outsourcing in the post-crisis era, at least for the study period 2008–2011.

Most developed economies, such as the USA, Japan, the UK, France, and Italy, experienced continuous shrinkage in international sourcing shares for the period of 1995–2011. Germany is one of the exceptions as it had expanded its share in 2000–2008, showing positive ECGS. Asia's four tigers had expanded shares mainly before 2005, but then started to shrink, whereas Taiwan and Hong Kong continuously dropped their shares from 2005 to 2011, and South Korea and Singapore first experienced a drop in 2005–2008 and then a rebound in 2008–2011. This is in line with the observations of Lehman (2012) that international sourcing firstly moves from the developed world to Asia's Four tigers and then to China. Unfortunately, until 2011 there was no evident sign that the international sourcing center had moved further toward less developing economies.

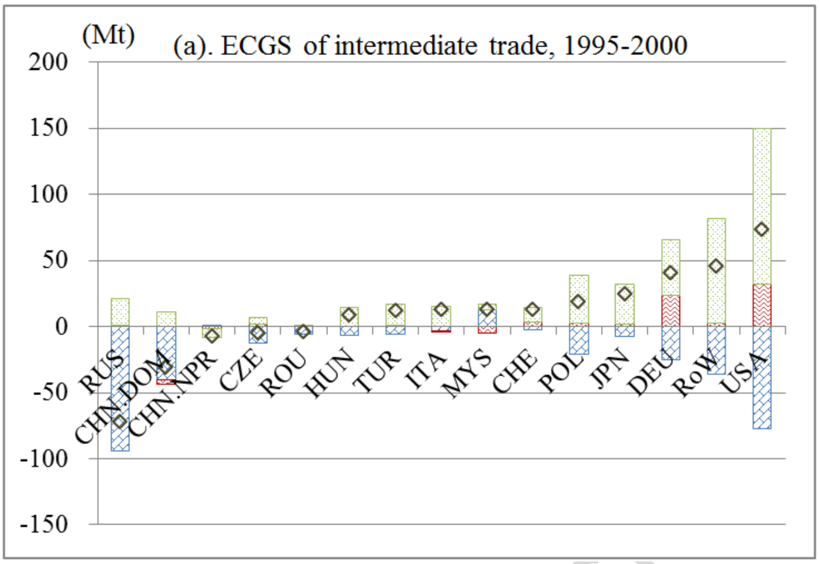
3.3. Global emissions cost of geographic shift in international sourcing by sourcing region, 1995–2011

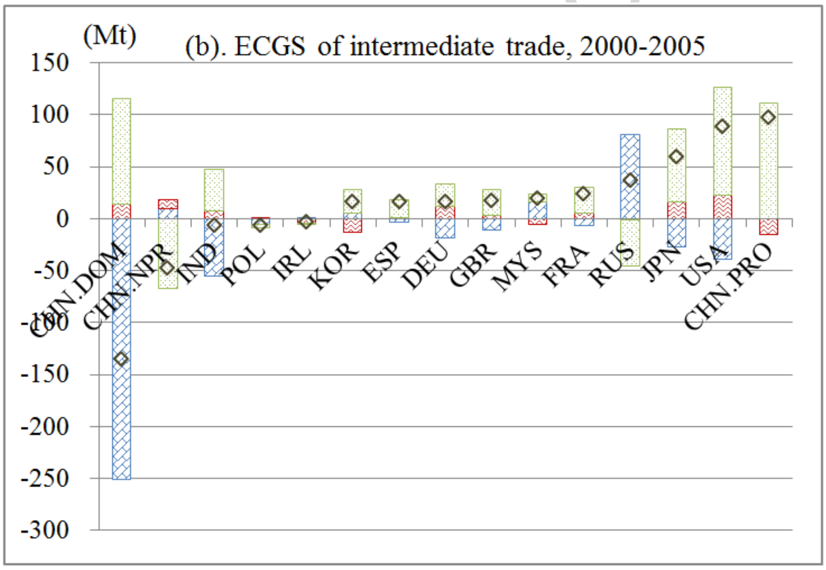
In figures 3 and 4 we present the ECGS of trade in intermediate and final products by sourcing region for the entire period of 1995–2011, measured by the summation $\sum_r ECGS_{t1}^{rs}\_III$ in eq. A.8 and $\sum_r ECS_{t1}^{rs}\_IV$ in eq. A.10, respectively. More specifically, we summarize the emission costs across region *r* into domestic, OECD economies, and non-OECD economies' emission costs, where their summation is the total emission cost due to the shift in the sourcing region *s*. Positive cost of non-OECD economies, for example, suggested the sourcing region *s* purchase more products, especially carbon-intensive products from non-OECD economies that are normally with high emission intensities. In contrast, negative cost of non-OECD economics suggested the sourcing region *s* purchased less products from non-OECD economies. In general, positive total emission cost suggested the sourcing region *s* purchase more products especially carbon-intensive products from economies with high emission intensities (mainly developed economies) rather than economies with low emission intensities (mainly developing economies). As most developing economies increased their shares in global trade, there are more outsourcing regions showing positive ECGS rather than regions showing negative ECGS. To simplify the analysis, we only present the top regions with the highest and the lowest ECGS.

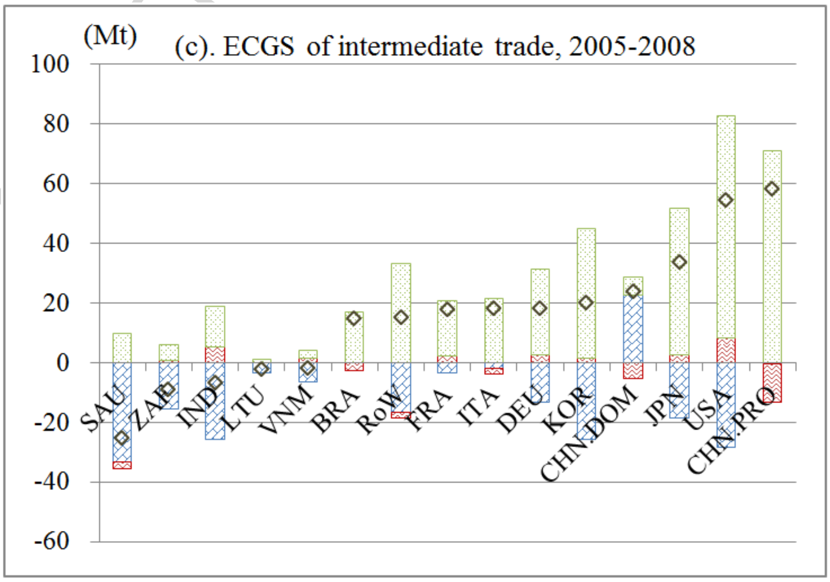
The few regions showing negative ECGS are mainly developing economies, including China, Russia, India, and Saudi Arabia (fig. 3). When using imported rather than domestic intermediates, their changing pattern of sourcing decreased their own emissions, and increased the emissions in other OECD and non-OECD economies for the entire period 1995–2011. Because their intensities are higher than OECD economies and most-OECD economies, such temporal changes brought negative ECGS for the global emissions.

Most developed economies show positive ECGS for the entire period 1995–2011. By outsourcing intermediates to other economies, especially non-OECD economies, they brought positive ECGS for the global emissions. Among them, the USA, Japan, Germany, France, Italy, and South Korea have often been the top outsourcing economies, showing relatively high ECGS for each of the four intervals. These large developed economies dominated the trend of the international sourcing pattern through a variety of ways, e.g., offshoring, FDI, and multi-national co-operations (MNCs). To find lower labor costs they have outsourced their intermediates and final products to developing economies, for which the global emissions had been increased.

China's three types of production show different dynamics in terms of intermediate use. Processing exports increasingly use imported materials from non-OECD economies rather than OECD economies for the entire period 1995–2011, and have showed considerable positive ECGS. In contrast, before 2005 non-processing exports tend to use more domestically produced intermediates or imported materials from OECD economies, leading to negative ECGS for the period 1995-2005; after 2005 non-processing exports also start to use more imported materials from non-OECD economies, with positive ECGS. Until 2005, the domestic productions used more domestic intermediates to replace imports; after the international crisis in 2008, the domestic productions started to use more domestic intermediates, showing considerable positive ECGS. The increasing requirement on imports from OECD economies might be driven by the upgrading of Chinese manufacturing from labor-intensive toward high-tech products, while the growing requirement on domestic intermediates might be driven by infrastructure and housing construction initiated by China, especially after the international crisis in 2008 (see Guan et al., 2014 or Jiang et al., 2016).


(Mt)
(a). ECGS of intermediate trade, 1995-2000
200
150
100
50
0
-50
-100
-150
RUS
CHN.DOM
CHN.NPR
CZE
ROU
HUN
TUR
ITA
MYS
CHE
POL
JPN
DEU
RoW
USA


(Mt)
(b). ECGS of intermediate trade, 2000-2005
150
100
50
0
-50
-100
-150
-200
-250
-300
CHN.DOM
CHN.NPR
IND
POL
IRL
KOR
ESP
DEU
GBR
MYS
FRA
RUS
JPN
USA
CHN.PRO


(Mt)
(c). ECGS of intermediate trade, 2005-2008
100
80
60
40
20
0
-20
-40
-60
SAU
ZAF
IND
LTU
VNM
BRA
RoW
FRA
ITA
DEU
KOR
CHN.DOM
JPN
USA
CHN.PRO

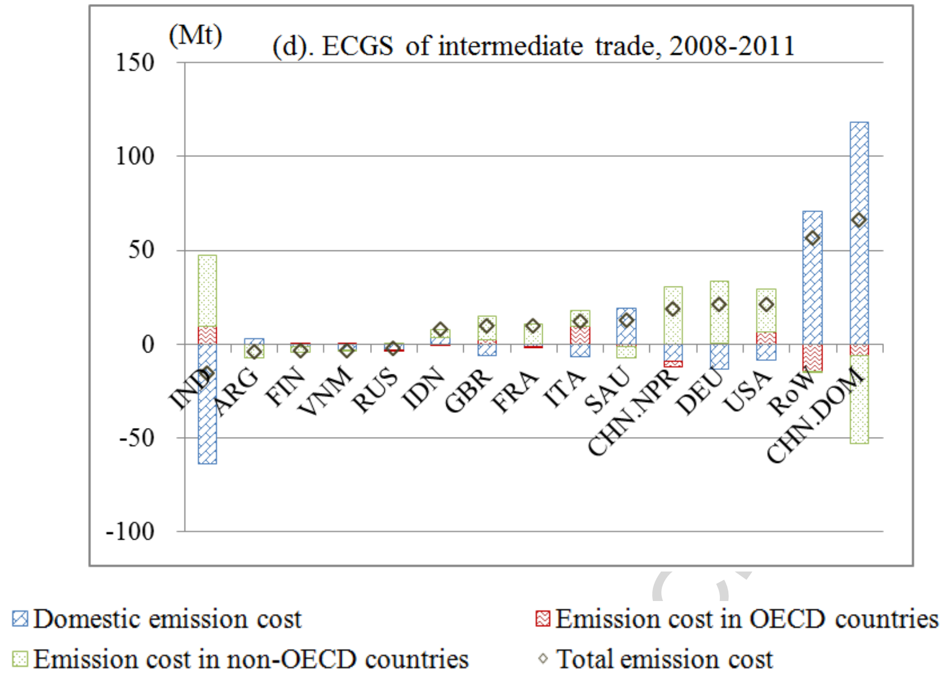
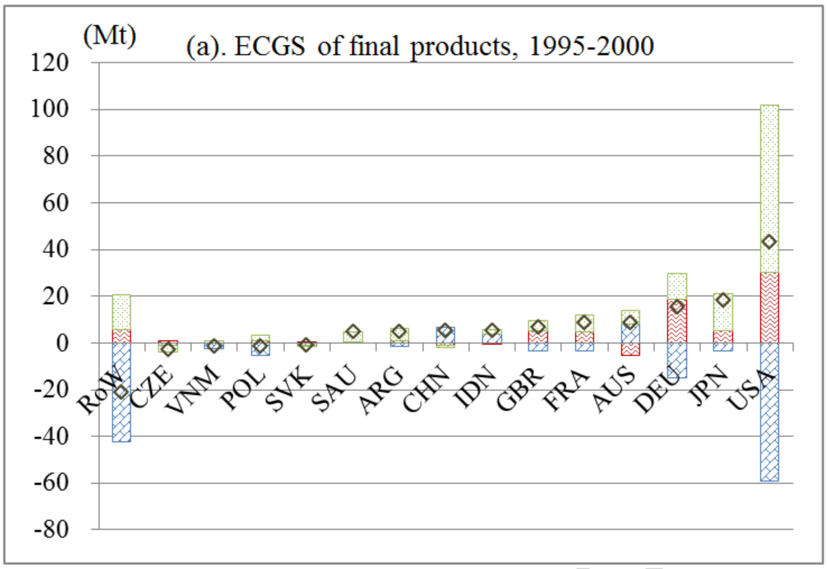
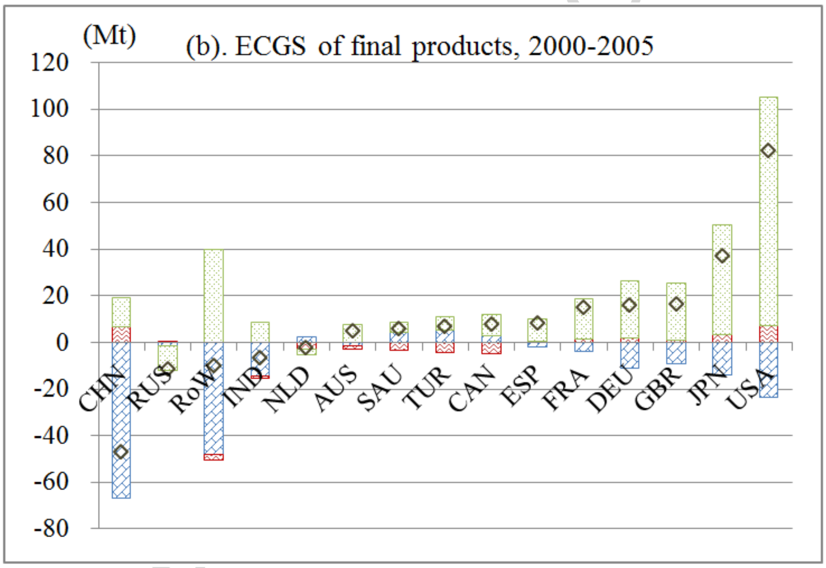


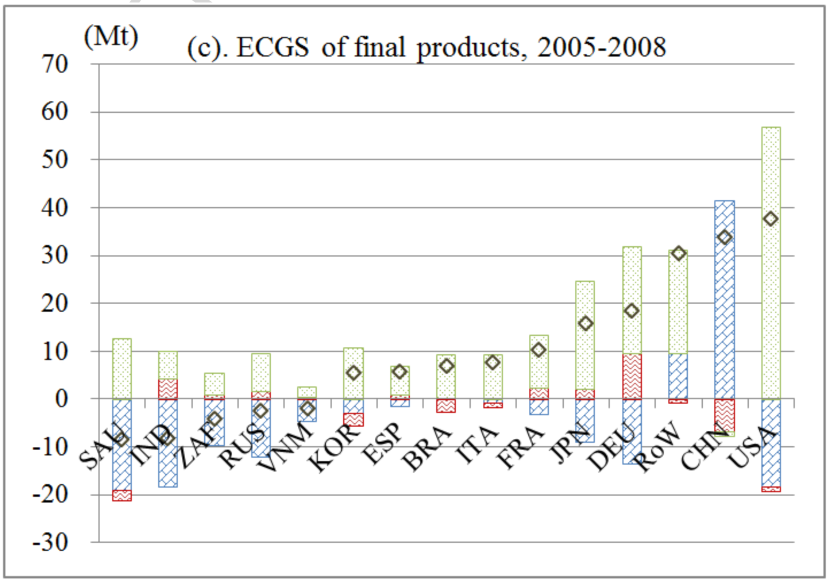
Figure 3. The emission cost of geographic shift of sourcing in intermediate products, by sourcing region, 1995–2011

The ECGS of sourcing in final products shows a very similar pattern to that of the intermediates, although in a smaller amount as a consequence that intermediate goods are more intensive in emissions than the final goods. Few large developing economies, such as India, Russia, and Saudi Arabia, show negative ECGS because the sourcing in final demands is moving toward domestic production for the period 1995–2008. In contrast, large developed economies such as the USA, Japan, and Germany still possess the biggest positive ECGS by outsourcing final consumptions toward developing economies.

In spite of the similarity, the ECGS patterns of sourcing in final products still have difference with that of intermediates. China turned to using more domestic intermediates and less imports from both OECD and non-OECD economies in 2008–2011. In terms of final products, however, China turned to using more final products from non-OECD economies but less final products from OECD economies. South Korea turned to using more intermediates but less final products from OECD economies for the period 2005–2011. This reflected a change in consumer preference.


(Mt)
(a). ECGS of final products, 1995-2000
120
100
80
60
40
20
0
-20
-40
-60
-80
RoW
CZE
VNM
POL
SVK
SAU
ARG
CHN
IDN
GBR
FRA
AUS
DEU
JPN
USA


(Mt)
(b). ECGS of final products, 2000-2005
120
100
80
60
40
20
0
-20
-40
-60
-80
CHN
RUS
RoW
IND
NLD
AUS
SAU
TUR
CAN
ESP
FRA
DEU
GBR
JPN
USA


(Mt)
(c). ECGS of final products, 2005-2008
70
60
50
40
30
20
10
0
-10
-20
-30
SAU
IND
ZAF
RUS
VNM
KOR
ESP
BRA
ITA
FRA
JPN
DEU
RoW
CHN
USA

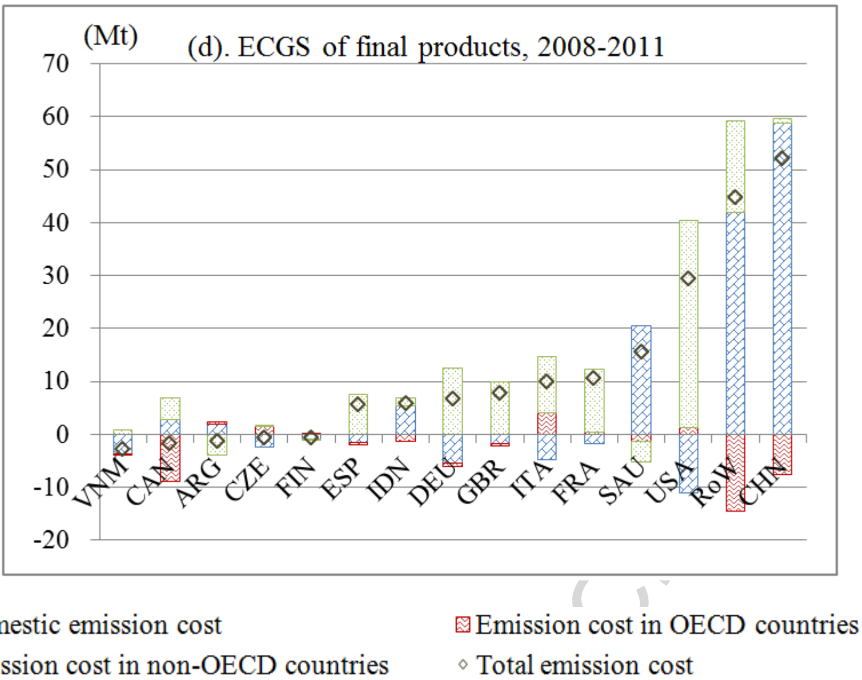


Figure 4. The emission cost of geographic shift of sourcing in final products, by sourcing region, 1995–2011

At the aggregate level, the ECGS due to the changing sourcing in intermediates has kept growing from 1995 to 2008, at 246 Mt for 1995–2000, 285 Mt for 2000–2005, and 323 Mt for 2005–2008; then, it dropped to 268 Mt for 2008–2011. In contrast, the ECGS due to the changing sourcing of final products has kept growing even in the post-crisis era, at 147 Mt for 1995–2000, 174 Mt for 2000–2005, 197 Mt for 2005–2008, and 231 Mt for 2008–2011[5]. As aforementioned, the trade pattern in intermediates is highly dominated by an active shift of developed economies toward low labor costs through offshoring and MNCs. Against the background of a high unemployment rate and sluggish demand, many developed economies may turn to purchasing more intermediates domestically after the crisis. As a result, we observed a much smaller domestic ECGS for the sourcing of intermediates of developed economies for the period 2008–2011 than the previous sub-periods (fig. 3). The purchase of final products however, is, to a great extent, dominated by the consumer preference and, thus, is less influenced by the crisis.

3.4. The global emissions cost of geographic shift in international sourcing, by industry, 1995–2011

In figure 5 we present the global emission cost due to the geographic shift of international sourcing pattern by industry for the four intervals (measured by $\sum_r \sum_s ECGS_{t1}^{rs}\_IV$ in eq. A.12). A positive cost suggested that worldwide the industry purchases more intermediates or final products

[5] The aggregate ECGS of trade in intermediates do not equal to the summation as shown in figure 3 because the decomposition of A-matrix is non-additive. The aggregate ECGS of trade in final products however equals to the summation as shown in figure 4 because the decomposition of final demand is additive.

from regions with high emission intensities (mainly developing economies) rather than regions with low emission intensities (mainly developed economies). Again, as most developed economies shrunk shares in global trade in general, only very few industries show negative ECGS, and the degrees are relatively small (less than 1.5 Mt for each interval). To simplify the analysis, we only present the top 10 industries with the highest positive ECGS.

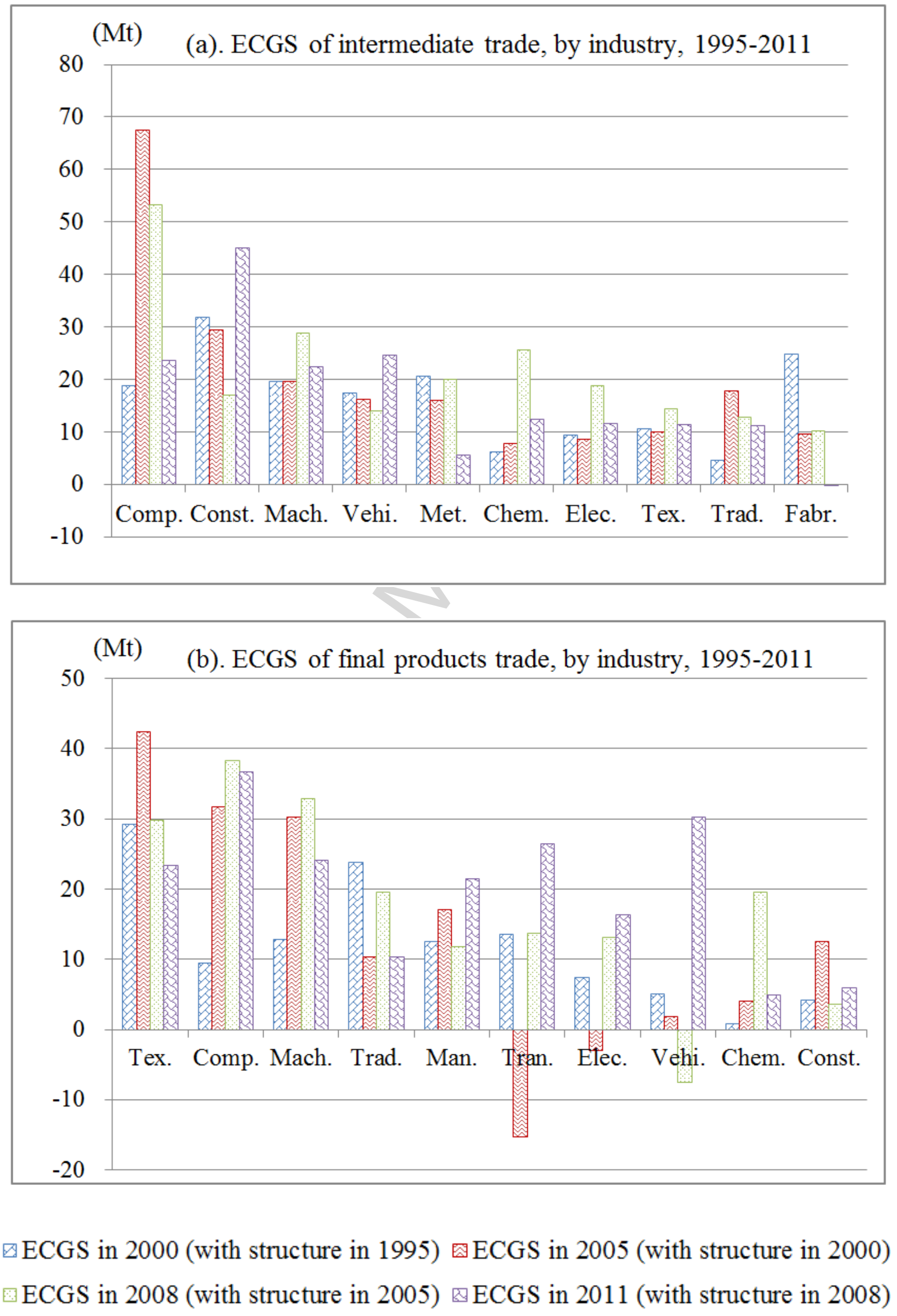


Figure 5. The emission cost of geographic shift of sourcing, by industry, 1995–2011.

Industry code: Tex. = Textiles, textile products, leather and footwear; Chem. = Chemicals and chemical products; Met. = Basic metals; Fab. = Fabricated metal products; Mach. = Machinery and equipment, nec; Comp. = Computer, electronic and optical equipment; Elec. = Electrical machinery and apparatus, nec; Vehi. = Motor vehicles, trailers and semi-trailers; Man. = Manufacturing nec; recycling; Const. = Construction; Trad. = Wholesale and retail trade; repairs; Tran. = Transport and storage.

The geographic shift of international sourcing in ICT goods (industry -- Computer, electronic and optical equipment) and machinery (industry -- Machinery and equipment, nec) brought the largest ECGS in terms of both intermediates and final products. The geographic shift of the sourcing pattern of intermediate and final products in ICT goods and machinery together lead to increases of 61 Mt, 149 Mt, 153, and 81 Mt CO_2 emissions for the four intervals 1995–2000, 2000–2005, 2005–2008, and 2008–2011, respectively. A further investigation shows that China has played increasing role as a recipient of sourcing: the geographic shift of sourcing in ICT goods and machinery together has increased China's emissions by 5 Mt, 115 Mt, 184 Mt, and 72 Mt for the corresponding four intervals. Although ICT goods and machinery are "clean" high-tech products themselves, the production of their raw materials emit a considerable amount of CO_2. From a perspective of production chains, the geographic shift of the production of ICT goods and machinery from developed economies toward China has led global CO_2 emissions to increase significantly (see also Jiang and Liu, 2015).

The geographic shift of sourcing in the production of textiles (industry -- Textiles, textile products, leather and footwear), chemical products (industry -- Chemicals and chemical products), vehicles (industry -- Motor vehicles, trailers and semi-trailers), and electrical products (industry -- Electrical machinery and apparatus, nec) also brings with it a considerable increase in global emissions, showing positive ECGS. Among them, the shift in the sourcing pattern of chemicals and vehicles mainly occur in the intermediates, leading to an ECGS of around 25–40 Mt together for each sub-period in 1995–2011. The shift of sourcing pattern of textiles and electrical products mainly occurs in the final products, leading to an ECGS around 37–43 Mt for the sub-period in 1995–2011. The fact that mainly non-energy intensive goods are responsible for the increase in emissions from trade is consistent with the results found by Davis et al. (2010). In addition, the shift of sourcing in basic metals, fabricated metals, and construction mainly occur in intermediates, while the shift of wholesale and retail trade, transport and storage mainly occur in final products.

3.5 Discussion of the results

The above analysis provides a what-if scenario study, wherein the global CO_2 emissions of 2011 are compared with those from the scenarios that assume the geographic shift did not occur for the period 1995–2010 and the global final demand remained the same. We also distinguish the sourcing economy/industry, and quantify their *direct* influence on global CO_2 emissions (refer as emission cost here). However, it should be noted that such a what-if scenario bears natural drawbacks as if it did, the world economy and trade volume would not have been the way it evolved. For example, if we assume the pattern of international sourcing in 2011 were as that in 1995, the world income distributions among developed and developing economics would not have been the way as that in 2011, and the global final demand as well as the trade volume would not remain the same. More explicitly, as developing economics expanded their shares in global trade of both intermediate and final products from 1995 to 2011, one reasonable expectation would be that the value-added developing economies received from global production chains would be much lower if we assume that the global trade pattern of 2011 remained as that it did in 1995. As a consequence, their demand on both domestic and foreign final products would be lower. In contrast, the value-added developed economies received from global production chains might be higher as they would have higher share in global trade of intermediate and final products.

In this context, our above measurement of ECGS is more like a discussion on *direct* effect of geographic shift of sourcing on global CO_2 emissions, and it could only become complete if we include the discussion on the effect of geographic shift of sourcing on global economy and final demand, and the subsequent *indirect* effect on CO_2 emissions. The changing distribution of value-added would lead that non-OECD economies had lower final demand (incl. consumptions and investment) and OECD economies had higher final demand in general, and this may further lead lower global trade volume. Still use the above two-country model where China is country A and the developed world is country B. Assume the world's total demand is changed from y^{t1} to $\widetilde{y^{t1}}$, the shares of country A and B in world final demand are changed from $fs_m^t\ (m = A, B)$ to $\widetilde{fs_m^t}(m = A, B)$, and the consumption-based emission intensities of country A and B are changed from $e_m^t(m = A, B)$ to $\tilde{e}_m^t(m = A, B)$, the *indirect* influence on global CO_2 emissions due to changing trade pattern from year *t*0 to *t*1 would be:

$$E\widetilde{CGS}_{t1} = e_A^{t1} fs_A^{t0} y^{t1} + e_B^{t1} fs_B^{t0} y^{t1} - \widetilde{e_A^{t1}}\widetilde{fs_A^{t0}}\widetilde{y^{t1}} - \widetilde{e_B^{t1}}\widetilde{fs_B^{t0}}\widetilde{y^{t1}} \quad (16)$$

where developed country B would have larger final demand as $\widetilde{fs_B^{t0}}\widetilde{y^{t1}} > fs_B^{t0} y^{t1}$ and China (developing country A) would have smaller final demand as $\widetilde{fs_A^{t0}}\widetilde{y^{t1}} < fs_A^{t0} y^{t1}$. The consumption-based emission intensities are however decided by the structure, for which developed and developing economies have clear difference. In fig. 6 we divide the industries into four major categories (i.e., Agriculture, Manufacturing, Construction and Services) and compare the structure of final demand (incl. consumptions and investment) by OECD and non-OECD economies in 1995 and 2011. In general, OECD economies incline to consume more services and less manufacturing and construction than non-OECD economies, and such a difference sustained over 1995-2011. The lower demand by OECD economies and higher demand by non-OECD economies thus imply more demand in services and demand in manufacturing goods and constructions in global totals. As a result, in eq. 16 the net (negative) value of $e_B^{t1} fs_B^{t0} y^{t1} - \widetilde{e_B^{t1}}\widetilde{fs_B^{t0}}\widetilde{y^{t1}}$ would be smaller than the net (positive) value of $e_A^{t1} s_A^{t0} y^{t1} - \widetilde{e_A^{t1}}\widetilde{fs_A^{t0}}\widetilde{y^{t1}}$. As a result, the $\widetilde{ECGS}_{t1}$ in eq. 16 would be always positive. That implies, if we considered the fact that geographic shift of sourcing stimulated the economic growth and consumptions in developing economies, there is potentially even larger influence of geographic shift of sourcing on global CO_2 emissions.

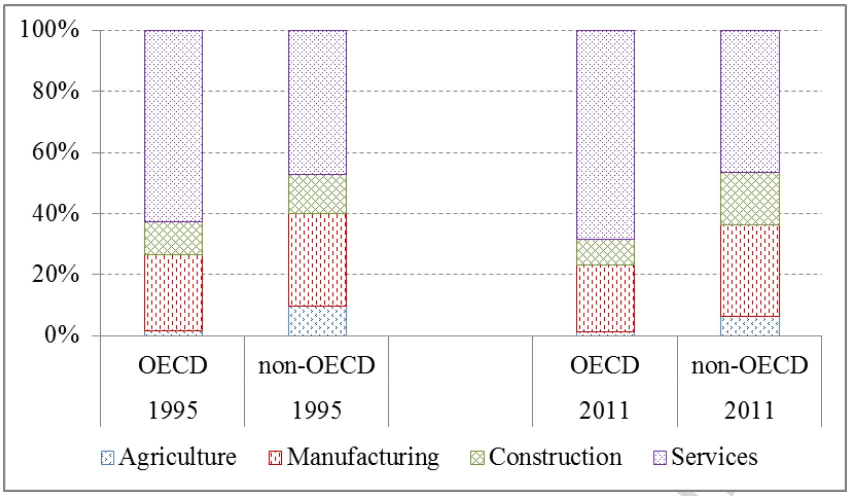


Figure 6. The structure of final demand by OECD and non-OECD economies, 1995 and 2011

4. Summary and policy implications

In this paper, we discussed the *direct* impact of geographic shift of international sourcing on global CO_2 emissions by adopting a scenario analysis that assumed the geographic shift did not occur for the period 1995–2011 and the others remained unchanged. In additions to the literatures that adopted structural decomposition analysis (SDA) or pollution haven hypothesis (PHH) focusing on both temporal changes of trade structure and trade volume, our analysis isolated the impact of changing trade structure on the global CO_2 emissions growth based on a what-if thought experiment. Our simulations indicate that, in 2011, had the share of trade by the sourcing economy remained at the level of 1995 and the global final demand remained unchanged as it had in 2011, global CO_2 emissions in production processes would have been 27.04 Gt, rather than the "actual" level of 29.85 Gt. In other words, the direct emission cost of the geographic shift (ECGS) in international outsourcing toward developing economies increased the annual global CO_2 emissions, in 2011, by 2.81 Gt from 1995 to 2011.

We also discuss from and to which country/region the ECGS is generated. In general, the developed economies increasingly outsourced their production, especially carbon-intensive intermediates, into developing economies. As a result, we observed positive ECGS in developing economies and negative ECGS in developed economies, mainly led by the changes of international sourcing of developed economies. By industry, the so-called high-tech products such as ICT goods, machinery, and electrical products, compose the largest share of ECGS. Although the production of high-tech products are relatively "clean" in terms of emission intensity, their production chain of raw materials and the related geographic shift toward developing economies, especially China, has considerably increased global CO_2 emissions.

In addition, there is potentially even larger influence of geographic shift of sourcing on global CO_2 emissions, as such a shift stimulated the economic growth and consumptions in developing economies, consequently this would bring additional energy demand and CO_2 emissions. It should be noted, however, that such economic growth and income rising is very fundamental for developing economies, in the sense they helped to raise living standard and literally pulled hundreds of millions, possibly billions, of people out of poverty in developing world. In other words, while the global CO_2 emissions would be much lower without the geographic shift of sourcing, the developing world would suffer from slower economic growth, worsen poverty reduction and poorer living standard as well.

In this context, our findings on the emission cost of geographic sourcing shift based on a what-if scenario analysis provide important implications for global climate change mitigations. On one hand, the geographic sourcing shift toward developing world would always bring positive emission cost as long as the emission intensity gap between developed and developing economies sustained. In 1995, the average CO_2 emission intensity per GDP using purchasing power parities (PPP) of OECD economies in 1995 was 0.44 kg CO_2 / US dollar in 2005 prices, 38.0% lower than that of non-OECD economies at 0.70 kg CO_2 / US dollar in 2005 prices; until 2011, the emission intensity gap had increased to 41%, when that of OECD and non-OECD economies are 0.33 and 0.55 kg CO_2 / US dollar in 2005 prices (IEA, 2014). On the other hand, the geographic sourcing shift that seeks lower labor and land costs in developing world indeed helped to reduce their poverty and increase their living standard. And more important, the shift is not over. There are signs that international sourcing is moving toward even less-developing economies in South Asia and Africa to seek lower labor costs (Stratfor, 2013; AfDB, OECD and UNDP, 2014). This can have a temporarily positive effect on the reduction of emissions by international trade, as these countries use pollution technology that is currently more efficient than China (Arce et al., 2016). But as long as the gap of emission intensity between developing countries and developed counties exists, such geographic shift would bring net global emissions growth in long-run.

Therefore, against the necessity of continuous geographic shift of sourcing to reduce poverty and increase income in developing world, and the sustained emission intensity gap, the global climate change mitigation requires stronger energy technology breakthroughs, especially ones developed by or transferable to the developing world. Such breakthroughs may include that make possible globally scalable, dense, and dispatchable on demand, low carbon energy, ones that are as applicable to the developing world as to the developed one. More specifically, the origin and destination of trade that has generated the largest ECGS point in the direction of which economies and in which sectors energy and technology breakthroughs must be applied so that international trade does not continue to increase emissions. Without such breakthroughs, the 2C degree of global warming limit set by the Paris Agreement will be very difficult to achieve.

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Appendix A. The estimations of emission cost of geographic shift in international sourcing (ECGS)

To simulate the emission cost of geographic shift, i.e., the impact of changing structure of international trade on global CO_2 emissions, our first step is Our first step is therefore to isolate the change in the structure of international trade, i.e., the pattern of international sourcing. In this paper, we follow the line with Xu and Dietzenbacher (2014), Arto and Dietzenbacher (2014), and Hoekstra et al. (2016), and decompose the **A**-matrix into technical coefficients and pattern of international sourcing. That is, define the total technical input coefficients of industry *j* (=1,...,34) in region *s* (=1,...,65) from industry *i* (*i*-input, *i* = 1,...,34) as $a_{ij}^{*s} = \sum_r a_{ij}^{rs}$. In matrix form, the technical input coefficients of region s would be $\mathbf{A}^{*s} = \begin{bmatrix} a_{11}^{*s} & \cdots & a_{1m}^{*s} \\ \vdots & \ddots & \vdots \\ a_{m1}^{*s} & \cdots & z_{mm}^{*s} \end{bmatrix}$ as a 34×34 matrix. Then, if we horizontally stack the $\mathbf{A}^{*s}$ matrices and further vertically stack the result 65 times, we would have $\mathbf{A}^{*} = \begin{bmatrix} \mathbf{A}^{*1} & \cdots & \mathbf{A}^{*n} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{*1} & \cdots & \mathbf{A}^{*n} \end{bmatrix}$ as a 2210×2210 matrix. $\mathbf{A}^{*}$ represents the technical intermediate input coefficient irrespective of the sourcing region.

Let $c_{ij}^{rs} = a_{ij}^{rs} / a_{ij}^{*s}$ indicate the share sourced from region *r* (=1,...,65) in the input a_{ij}^{*s} in region *s* (=1,...,65), then in the matrix form, we would have $\mathbf{C}^{rs} = \begin{bmatrix} c_{11}^{rs} & \cdots & c_{1m}^{rs} \\ \vdots & \ddots & \vdots \\ c_{m1}^{rs} & \cdots & c_{mm}^{rs} \end{bmatrix}$ as a 34*34 matrix (where $\sum_r c_{ij}^{rs} = 1$), and $\mathbf{C} = \begin{bmatrix} \mathbf{C}^{11} & \cdots & \mathbf{C}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{C}^{n1} & \cdots & \mathbf{C}^{nn} \end{bmatrix}$ as a 2210×2210 matrix, to reflect the pattern of international sourcing. Then the A-matrix can be decomposed as

$$\mathbf{A} = \mathbf{C} \otimes \mathbf{A}^{*} \tag{A.1}$$

where $\otimes$ stands for the Hadamard product.

Moreover, we can split the **C**-matrix into sub-matrices for each region s (=1,...,65). By letting $\mathbf{C}^{S} = \begin{bmatrix} 0 & \cdots & \mathbf{C}^{1s} & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & & \mathbf{C}^{ss} & & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{C}^{65,s} & \cdots & 0 \end{bmatrix}$, we would have $\mathbf{C} = \sum_s \mathbf{C}^{S}$. The Leontief inverse can be rewritten as

$$\mathbf{B} = [\mathbf{I} - (\textstyle\sum_s \mathbf{C}^{S}) \otimes \mathbf{A}^{*}]^{-1} \tag{A.2}$$

In a similar fashion, the final demand can be decomposed into the determinants of total final demand and the pattern of sourcing. Let $y_i^{*s} = \sum_r y_i^{rs}$ indicate the total final demand in region *s* for output of industry *i* from all source regions, $f_i^{rs} = y_i^{rs}/y_i^{*s}$ indicate the share sourced from region r (=1,...,65) in the final demand of region s (=1,...,65) for output in industry *i* (=1,...,34), and define the matrices correspondingly, the final demand can be decomposed as

$$\mathbf{F} = [\sum_s \mathbf{F}^S] \otimes \mathbf{Y}^* \quad \text{(A.3)}$$

The second step is to introduce scenario analysis to quantify the emission cost. Letting subscript t1 denote the year *t1*, actual emission (Scenario I) can be calculated as:

$$\begin{bmatrix} \mathbf{E}_{t1}^{11} & \cdots & \mathbf{E}_{t1}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{E}_{t1}^{n1} & \cdots & \mathbf{E}_{t1}^{nn} \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{CA}}_{t1}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{CA}}_{t1}^{n} \end{bmatrix} \cdot [\mathbf{I} - (\sum_s \mathbf{C}_{t1}^{s}) \otimes \mathbf{A}_{t1}^{*}]^{-1} \cdot (\sum_s \mathbf{F}_{t1}^{s}) \otimes \mathbf{Y}_{t1}^{*} \quad \text{(A.4)}$$

Scenario II assumes that the global final demands $\mathbf{Y}^*$, production technique $\mathbf{A}^*$ and emission intensity $\mathbf{CA}^r$ (r =1,...,65) remain unchanged, and the structure of international trade by sourcing region is replaced by those structures in year *t0*, then the production-based CO_2 emissions in Scenario II can be calculated as:

$$\begin{bmatrix} \mathbf{E}_{t1}^{11}\_\mathrm{II} & \cdots & \mathbf{E}_{t1}^{1n}\_\mathrm{II} \\ \vdots & \ddots & \vdots \\ \mathbf{E}_{t1}^{n1}\_\mathrm{II} & \cdots & \mathbf{E}_{t1}^{nn}\_\mathrm{II} \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{CA}}_{t1}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{CA}}_{t1}^{n} \end{bmatrix} \cdot [\mathbf{I} - (\sum_s \mathbf{C}_{t0}^{s}) \otimes \mathbf{A}_{t1}^{*}]^{-1} \cdot (\sum_s \mathbf{F}_{t0}^{s}) \otimes \mathbf{Y}_{t1}^{*} \quad \text{(A.5)}$$

The emission cost in region *r* and year *t1* due to the geographic shift of international sourcing for the period t0-t1 would be:

$$ECGS_{t1}^{r}\_II = \sum_s E_{t1}^{rs} - \sum_s E_{t1}^{rs}\_II \quad \text{(A.6)}$$

where $ECGS_{t1}^{r}\_II > 0$ suggests that the world is inclined to purchase more intermediate or/and final products from region *r* (directly and indirectly), and vice versa. To sum up, the $ECS_{t1}^{r}\_II$ over region *r* (=1,...,65) would give the global emission cost due to the geographic shift of international sourcing for the period t0-t1. At the aggregate level, $ECGS_{t1}\_II = \sum_r ECGS_{t1}^{r}\_II > 0$ suggests that the world is inclined to purchase more intermediate or/and final products from economies with higher emission intensities (mostly developing economies). For example, China has highly relied on coal as its primary energy input, and as a result its CO_2 emission intensity per US$ GDP in constant price has been around 1.8–2.0 times that of the world average (IEA, 2014). When China's exports account for more of the share of the world total, that is, the world is inclined to purchase more products (incl. intermediate and final products) from China rather than from the economies with lower emission intensities, there are additional CO_2 emissions, called the emission cost of the geographic shift in international sourcing (i.e. ECGS) in this paper.

The emission cost can also be traced by source region and product type. In Scenario III, we assume that the structure of international trade of intermediates in region *s* is replaced by those structured in year *t0*, and the others remain unchanged. Then, the production-based CO_2 emissions in Scenario III can be calculated as

$$\begin{bmatrix} \mathbf{E}_{t1}^{11}\_III & \cdots & \mathbf{E}_{t1}^{1n}\_III \\ \vdots & \ddots & \vdots \\ \mathbf{E}_{t1}^{n1}\_III & \cdots & \mathbf{E}_{t1}^{nn}\_III \end{bmatrix}$$

$$= \begin{bmatrix} \widehat{\mathbf{CA}}_{t1}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{CA}}_{t1}^{n} \end{bmatrix} \cdot \left\{\mathbf{I} - \left[\sum_{k=1,..,65;k\neq s}(\mathbf{C}_{t0}^{s} + \mathbf{C}_{t1}^{k})\right] \otimes \mathbf{A}_{t1}^{*}\right\}^{-1} \cdot (\sum_{s} \mathbf{F}_{t1}^{s}) \otimes \mathbf{Y}_{t1}^{*} \tag{A.7}$$

The emission cost in region *r* and year *t1*, due to the geographic shift of international sourcing pattern of intermediate in region *s* for the period *t0*-*t1*, would be:

$$ECGS_{t1}^{rs}\_III = E_{t1}^{rs} - E_{t1}^{rs}\_III \tag{A.8}$$

If we summarize $ECGS_{t1}^{rs}\_III$ across region *r* according to its type (i.e. domestic, other OECD or non-OECD countries), then the emission cost domestically, in OECD countries and non-OECD countries due to the geographic shift of international sourcing of intermediate in region *s* can be further calculated.

Similarly, in Scenario IV, we assume that the structure of international trade of final demand in region *s* is replaced by those structured in year *t0*, and the others remain unchanged, then the production-based CO_2 emissions in Scenario IV can be calculated as:

$$\begin{bmatrix} \mathbf{E}_{t1}^{11}\_IV & \cdots & \mathbf{E}_{t1}^{1n}\_IV \\ \vdots & \ddots & \vdots \\ \mathbf{E}_{t1}^{n1}\_IV & \cdots & \mathbf{E}_{t1}^{nn}\_IV \end{bmatrix}$$

$$= \begin{bmatrix} \widehat{\mathbf{CA}}_{t1}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{CA}}_{t1}^{n} \end{bmatrix} \cdot \{\mathbf{I} - (\sum_{s} \mathbf{C}_{t1}^{s}) \otimes \mathbf{A}_{t1}^{*}\}^{-1} \cdot \left[\sum_{k=1,..,65;k\neq s}(\mathbf{F}_{t0}^{s} + \mathbf{F}_{t1}^{k})\right] \otimes \mathbf{Y}_{t1}^{*} \tag{A.9}$$

The emission cost in region *r* and year *t1*, due to the geographic shift of international sourcing pattern of final products in region *s* for the period t0-t1, would be:

$$ECGS_{t1}^{rs}\_IV = E_{t1}^{rs} - E_{t1}^{rs}\_IV \tag{A.10}$$

In addition, the emission cost can be traced by the change of sourcing pattern of specific industry. Let $\mathbf{C}^{\mathrm{L}}$ indicate the share matrix of intermediate of *l*-th industry, filled with shares c_{kl}^{rs} (*k* =1,…,34; *r*, *s* =1,…,65) in the *l*-th (=1,…,34) industry and zeros for other industry *g* (≠ *l*), we would have $\mathbf{C} = \sum_{\mathrm{L}} \mathbf{C}^{\mathrm{L}}$. Similarly, if we let $\mathbf{F}^{\mathrm{L}}$ indicate the share matrix of final demand of *l*-th industry, the emission cost under Scenario V (structure of trade in intermediate and final products in industry *l* is replaced by those in year *t0*, and the others remain unchanged) can be quantified as

$$\begin{bmatrix} \mathbf{E}_{t1}^{11}\_V & \cdots & \mathbf{E}_{t1}^{1n}\_V \\ \vdots & \ddots & \vdots \\ \mathbf{E}_{t1}^{n1}\_V & \cdots & \mathbf{E}_{t1}^{nn}\_V \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{CA}}_{\mathbf{t1}}^{\mathbf{1}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \widehat{\mathbf{CA}}_{\mathbf{t1}}^{\mathbf{n}} \end{bmatrix} \cdot$$

$$\left\{\mathbf{I} - \left[\sum_{g=1,..,65;g\neq l}(\mathbf{C}_{t0}^{l} + \mathbf{C}_{t1}^{g})\right] \otimes \mathbf{A}_{t1}^{*}\right\}^{-1} \cdot \left[\sum_{g=1,..,65;g\neq l}(\mathbf{F}_{t0}^{l} + \mathbf{F}_{t1}^{g})\right] \otimes \mathbf{Y}_{t1}^{*} \tag{A.11}$$

$$ECGS_{t1}\_V = \sum_{r}\sum_{s} E_{t1}^{rs} - \sum_{r}\sum_{s} E_{t1}^{rs}\_V \tag{A.12}$$

Appendix table B. Region and Industry list

No.	Abbr.	Region	Group	No.	Industry
1	AUS	Australia	OECD	1	Agriculture, hunting, forestry and fishing
2	AUT	Austria		2	Mining and quarrying
3	BEL	Belgium		3	Food products, beverages and tobacco
4	CAN	Canada		4	Textiles, textile products, leather and footwear
5	CHL	Chile		5	Wood and products of wood and cork
6	CZE	Czech Republic		6	Pulp, paper, paper products, printing and publishing
7	DNK	Denmark		7	Coke, refined petroleum products and nuclear fuel
8	EST	Estonia		8	Chemicals and chemical products
9	FIN	Finland		9	Rubber and plastics products
10	FRA	France		10	Other non-metallic mineral products
11	DEU	Germany		11	Basic metals
12	GRC	Greece		12	Fabricated metal products
13	HUN	Hungary		13	Machinery and equipment, nec
14	ISL	Iceland		14	Computer, Electronic and optical equipment
15	IRL	Ireland		15	Electrical machinery and apparatus, nec
16	ISR	Israel		16	Motor vehicles, trailers and semi-trailers

17	ITA	Italy		17	Other transport equipment
18	JPN	Japan		18	Manufacturing nec; recycling
19	KOR	South Korea		19	Electricity, gas and water supply
20	LUX	Luxembourg		20	Construction
21	MEX.NGM	Mexico Non-Global Manufacturing		21	Wholesale and retail trade; repairs
22	MEX.GMF	Mexico Global Manufacturing		22	Hotels and restaurants
23	NLD	Netherlands		23	Transport and storage
24	NZL	New Zealand		24	Post and telecommunications
25	NOR	Norway		25	Financial intermediation
26	POL	Poland		26	Real estate activities
27	PRT	Portugal		27	Renting of machinery and equipment
28	SVK	Slovak Republic		28	Computer and related activities
29	SVN	Slovenia		29	R&D and other business activities
30	ESP	Spain		30	Public admin. and defence; compulsory social security
31	SWE	Sweden		31	Education
32	CHE	Switzerland		32	Health and social work
33	TUR	Turkey		33	Other community, social and personal services
34	GBR	United Kingdom		34	Private households with employed persons
35	USA	United States			

36	ARG	Argentina	non-OECD	
37	BGR	Bulgaria		
38	BRA	Brazil		
39	BRN	Brunei Darussalam		
40	CHN.DOM	China Domestic sales only		
41	CHN.PRO	China Processing		
42	CHN.NPR	China Non processing goods exporters		
43	COL	Colombia		
44	CRI	Costa Rica		
45	CYP	Cyprus		
46	HKG	Hong Kong SAR		
47	HRV	Croatia		
48	IDN	Indonesia		
49	IND	India		
50	KHM	Cambodia		
51	LTU	Lithuania		
52	LVA	Latvia		
53	MLT	Malta		
54	MYS	Malaysia		
55	PHL	Philippines		

56	ROU	Romania		
57	RUS	Russian Federation		
58	SAU	Saudi Arabia		
59	SGP	Singapore		
60	THA	Thailand		
61	TUN	Tunisia		
62	TWN	Chinese Taipei		
63	VNM	Viet Nam		
64	ZAF	South Africa		
65	RoW	Rest of the world		

The Global CO_2 Emission Cost of Geographic Shifts in International Sourcing

1. We simulated the global *direct* CO_2 emission cost of geographic shift of international sourcing.

2. Global CO_2 emissions would have been much lower without the geographic shift.

3. The geographic shift was mainly dominated by developed economies and occurred in high-tech industries.

4. The global climate change mitigation requires stronger energy technology breakthroughs, especially in the developing world.