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The emission cost of international sourcing: using structural decomposition analysis to calculate the contribution of international sourcing to CO_2-emission growth

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ABSTRACT

The effect of changes in trade patterns, particularly increasing international sourcing, on global CO_2-emissions growth has yet to be clearly understood. In this paper, we estimate the emission cost of sourcing (ECS), which originates from replacing domestic products by imports from countries with more CO_2-intensive technologies. Using a structural decomposition analysis, we find that changes in sourcing patterns between 1995 and 2007 contribute (1) to reducing territorial emissions in high-wage countries (70% of their territorial emissions growth) and (2) to increasing territorial emissions in low-wage countries (30% of their territorial emissions increase). The net global effect, the ECS, amounts to 18% of total global CO_2-emissions growth. Our results call the climate change policies based on territorial principles into question given that they disregard that differences in emission intensities between countries contribute to raising global emissions. In contrast, policies fostering the transfer of cleaner technologies to low-wage countries decrease the ECS.

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1. Introduction

Global CO_2 emissions have continued to rise over the past two decades despite private and public efforts to mitigate them. From 1995 until 2007,[1] the growth in global CO_2-emissions amounted to 7.4 Gigatons (Gt) (Blanco et al., 2014), of which 6.3 Gt were due to industrial activities (Timmer, 2012).[2] Most of this growth occurred in emerging or developing economies. In particular, China accounted for more than 40% of the worldwide CO_2-emission growth over this period.

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[1] Although the world input–output database (WIOD) that is used for the calculations here contains data up to 2009, we have restricted the analysis to the period 1995–2007 to avoid presenting results influenced by the 2008 financial and economic crisis.

[2] This includes emissions from energy use in production activities but not direct emissions from households.

In parallel to this increase in CO_2 emissions, there has been a rapid growth in international trade (6.1% per year on average between 1990 and 2007), which has largely exceeded gross world GDP growth (2.6%) over the same period (WTO, 2013a). Moreover, patterns of trade have also changed fundamentally. In geographic terms, the increasing participation of developing economies in international trade has reduced the share of international trade between developed economies (WTO, 2013b).[3] In terms of traded products, intermediate goods and services have become ever more important (Hummels et al., 2001; Sturgeon and Gereffi, 2009; De Backer and Yamano, 2012). Both these trends are directly related to the reorganization of production processes: ever greater fragmentation paving the way for the relocation of production stages particularly from high-wage to low-wage countries. This has led to a rapid increase in *international sourcing* of intermediate goods and services and to the emergence of global value chains (Sturgeon and Gereffi, 2009; OECD, 2013).

As emphasized by Baldwin (2011), developments in information and communication technologies have facilitated the coordination of production activities at a distance. Hence, the relocation of activities from high-wage countries to countries with lower wages has become even more profitable. While labour costs have always been the main driver of relocations, the North America Free Trade Agreement (NAFTA) negotiations in the early 1990s did spark an intense debate on whether unequal environmental regulatory standards and compliance costs across countries could be a source of comparative advantage for countries with loose regulations, which would thereby become 'pollution havens' (Daly, 1993). However, the empirical evidence – largely based on non-greenhouse gas (GHG) air pollutants data and environmental cost data – provided no or only weak support to the pollution haven hypothesis (PHH) (Grossman and Krueger, 1993; Wheeler, 2001; Jeppesen et al., 2002; Eskeland and Harrison, 2003; Brunnermeier and Levinson, 2004; Cole et al., 2005; He, 2006; Manderson and Kneller, 2012). The low share of environmental cost in total cost is often pointed out as the reason for the weak empirical support for the PHH (Ederington et al., 2005).

Although the empirical literature does not provide strong evidence that environmental regulation has exerted an influence on relocation and trade, changes in trade patterns and trade volume growth have had a considerable effect on the distribution of environmental pressures between countries, in particular for air emissions. Trade dissociates production and consumption, thereby allowing the transfer of the emission burden of production from one country to another (Felder and Rutherford, 1993; Kuik and Gerlagh, 2003). For GHG emissions, this is generally referred to as carbon leakage. Peters (2010) defines two types of carbon leakage. On the one hand, 'strong' carbon leakage corresponds to GHG emissions that occur abroad as a result of the more restrictive climate policy of a given home country, i.e. it is the increase in GHG emissions in 'pollution haven' countries. In line with empirical findings for the PHH, there is little evidence that 'strong' carbon leakage is actually significant (Peters, 2010). On the other hand, 'weak' carbon leakage takes emissions embodied in all international trade flows for a given country into account irrespective of whether these flows are prompted by its climate policy or not. Hence, it corresponds to GHG emissions that occur abroad in order to meet consumption in the country. 'Weak' carbon leakage has been quantified by calculating balances of CO_2 or GHG emissions embodied in trade for

[3] International trade between developed countries accounted for 56% of total international trade in 1990 but only 36% in 2011 (WTO, 2013b).

individual countries or country groupings based on input–output data and models (Wiedmann et al., 2007; Peters and Hertwich, 2008; Davis and Caldeira, 2010).[4] According to the results, developed countries are net importers of (embodied) GHG emissions from developing countries. Moreover, there has been an increase in CO_2-emissions embodied in international trade over the past couple of decades (Peters et al., 2011).

Overall, 'weak' carbon leakage from developed to developing countries is now well established in the literature. However, in line with the difference between 'strong' and 'weak' carbon leakage, Jakob and Marschinski (2013) emphasize that "observing so-called weak carbon leakage [...] should not be interpreted as sufficient evidence that trade has resulted in a net increase in emissions in the latter [i.e. in developing countries]" (22). The same holds also at the global scale, i.e. 'weak' carbon leakage does not necessarily imply a rise in global CO_2-emissions. Moreover, despite findings that 'weak' carbon leakage has grown over time (Peters et al., 2011)[5], work on the contribution of international trade (and other factors) to the *growth* in global CO_2-emissions remains scarce. In particular, the effect of *international sourcing* on global CO_2-emissions growth has not yet been quantified. The aim of this paper is to estimate this effect and to understand its implications for climate change policy. For this purpose, we use a decomposition method (structural decomposition analysis – SDA) in line with the ones developed by Oosterhaven and van der Linden (1997) and Arto and Dietzenbacher (2014). The method allows one to determine the influence of changes in consumption levels (economic growth), consumption patterns and technology on CO_2-emissions. The particular novelty of our contribution is to extend the method to isolate the effect of changes in sourcing patterns between different wage groups of countries. We calculate the contribution of these changes in sourcing patterns to changes in territorial CO_2-emissions of low-wage, medium-wage and high-wage countries, and sum these contributions to obtain the net effect at the global level, which we refer to as emission cost of sourcing (ECS).[6]

In particular, high-wage countries increasingly source goods and services from countries with lower wages. This has contributed to reducing their territorial CO_2-emissions, while increasing the territorial CO_2-emissions of lower wage countries. Given the differences in the CO_2-emission intensity of production, the territorial emission increase in lower wage countries due to the changes in international sourcing more than offsets the reduction in higher wage countries.[7] This is what we call the ECS. The implication is that changes in sourcing behaviour are not neutral with respect to global CO_2-emission growth.[8]

[4] The methodology has also been applied to other polluting emissions, land and water use and biodiversity (Serrano and Dietzenbacher, 2010; Steen-Olsen et al., 2012; Lenzen et al., 2013).

[5] Peters et al. (2011) show that net imports of (embodied) CO_2 by Annex B countries from non-Annex B countries of the Kyoto protocol has increased from 0.4 to 1.6 Gt between 1990 and 2008.

[6] This does not exclude a further rise in emissions when, as sourcing patterns change, a greater volume of intermediate goods is shipped over longer distances thereby generating a rise in emissions from transportation. This would be the emission cost of sourcing due to transportation.

[7] We deliberately refrain from grouping countries into Annex B and non-Annex B countries of the Kyoto protocol. Instead, we group countries based on wage differences. By doing so, we recognize the crucial influence of wage differences on international sourcing and quantify the contribution of sourcing to changes in CO_2-emissions given wage differences rather than differences in climate policy.

[8] This is in line with an observation made by Jakob and Marschinski (2013) regarding the change in the sourcing pattern between two countries (A and B): "the amount of emissions generated by substituting country B's imports from A with domestically produced goods will differ from the amount that were formerly generated for their production in country A" (p. 21).

In the remainder of the paper, we proceed as follows. The next section presents the environmentally extended multi-regional input–output (MRIO) model and the SDA as well as the data. A detailed discussion of the model is provided in the supplementary material. In Section 3, results of the application of the decomposition analysis are reported and interpreted. Conclusions are drawn in Section 4.

2. Method and data

2.1. Model

SDA is a decomposition method based on the input–output model. It allows one to quantify contributions to changes in output, income or other variables.[9] Technological change, population growth, consumption growth or changes in consumption patterns are among the common contributing factors. Recently, SDA has been increasingly applied to analyse the influence of trade on the growth in CO_2 or GHG emissions. Peters et al. (2007), Guan et al. (2008), Baiocchi and Minx (2010) and Minx et al. (2011) decompose changes in emissions for a single country.[10] Arto and Dietzenbacher (2014) analyse the changes in global GHG emissions using an SDA[11] based on a MRIO model.[12] Their SDA breaks down the change in global emissions into effects of per capita consumption growth, the product mix of final consumption, population growth and technology as well as a 'trade structure effect', which measures the contribution of changes in trade patterns for intermediates. In their results, only a fairly moderate share of the overall growth in global GHG emissions can be attributed to the trade structure.

The methodology used in this paper builds on the approach of Arto and Dietzenbacher (2014) deepening and adapting it to assess the effect that sourcing has on CO_2-emissions in low-wage, medium-wage and high-wage countries, as well as the net effect on global emissions. In other words, we investigate the possibility that changes in territorial emissions of single countries have been influenced by changes in trade or sourcing patterns, i.e. that changing sourcing patterns may contribute to explain the bias in the geographic distribution of the worldwide CO_2-emission growth towards developing economies. Therefore, compared to Arto and Dietzenbacher (2014), we further elaborate the model with respect to *international sourcing* patterns by breaking up the 'trade structure effect' into several components. This is based on the recognition that when the share of domestically sourced goods and services in consumption falls, that of internationally sourced goods and services

[9] Miller and Blair (2009) provide a detailed and complete explanation of the input–output model and standard SDA applications. Hoekstra (2005) and Su and Ang (2012) give an overview of SDA methods and applications for environmental variables.

[10] The issue of the effect of trade in intermediates on changes in a single country's emissions is also investigated in Michel (2013) using index decomposition rather than SDA.

[11] Oosterhaven and Van der Linden (1997) previously developed a similar SDA approach for analysing the contributions of changes in technology and trade structures to income growth in several European countries.

[12] Xu and Dietzenbacher (2014), Duarte et al. (2015) and Malik and Lan (2016) are other examples of MRIO-based SDA. The first decomposes the CO_2-emissions embodied in trade rather than total production-related emissions as in Arto and Dietzenbacher (2014). Duarte et al. (2015) is an application of SDA to water footprints while Malik and Lan (2016) decomposes global CO_2-emissions into all major decomposition effects. The first two studies are based on the WIOD while the latter is based on the Eora database. These are the only two MRIO databases that currently contain previous-year-price tables as required for the application of SDA. Finally, note that the analysis in Baiocchi and Minx (2010) actually also relies on an MRIO database, albeit on a two region one (the UK and the RoW).

necessarily rises. To take this into account, we distinguish domestic sourcing and sourcing from high-, medium- and low-wage countries.[13] Thereby, the compensating effects of changes in sourcing patterns on emissions are revealed and quantified, and the ECS is calculated as the sum of these effects.

The starting point of our approach is a standard environmentally extended MRIO model[14] with M countries or regions and N industries recording inter-country flows from source to sourcing country for both intermediate and final demand. Emissions ($\mathbf{u}$) are related to final demand ($\mathbf{y}^*$)[15] through emission intensities ($\mathbf{v}$) and the Leontief matrix $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$, where $\mathbf{A}$ is the multi-regional matrix of technical coefficients.

$$\mathbf{u} = \hat{\mathbf{v}}\mathbf{L}\mathbf{y}^*. \tag{1}$$

According to Equation 1, territorial emissions by industry and sourcing country, $\mathbf{u}$, are equal to all emissions directly and indirectly required to satisfy final demand. Further splitting up the Leontief and final demand matrices to highlight sourcing patterns yields:

$$\begin{aligned}\mathbf{u} = \left(\sum_s \hat{\mathbf{v}}^s\right) \times \underbrace{\left[\mathbf{I} - \left(\sum_s (\mathbf{C}^s_{\text{dom}} + \mathbf{C}^s_{\text{low}} + \mathbf{C}^s_{\text{med}} + \mathbf{C}^s_{\text{high}})\right) \otimes \left(\sum_s \mathbf{A}^{*s}\right)\right]^{-1}}_{\mathbf{L}=(\mathbf{I}-\mathbf{C}\otimes\mathbf{A}^*)^{-1}} \\ \times \underbrace{\left[\left(\sum_s (\mathbf{F}^s_{\text{dom}} + \mathbf{F}^s_{\text{low}} + \mathbf{F}^s_{\text{med}} + \mathbf{F}^s_{\text{high}})\right) \otimes \left(\left(\sum_s \mathbf{B}^s\right)\left(\sum_s \mathbf{y}^s\right)\right)\right]}_{\mathbf{y}^*=\mathbf{F}\otimes\mathbf{B}\times\mathbf{y}} \mathbf{e}.\end{aligned} \tag{2}$$

The matrix of technical coefficients ($\mathbf{A}$) is now a Hadamard product ($\otimes$) of the overall technical coefficients irrespective of the source country ($\mathbf{A}^*$) and intermediate sourcing shares by country and industry of origin ($\mathbf{C}$).[16] We further subdivide $\mathbf{C}$ for each sourcing country s according to the origin of the intermediates: $\mathbf{C}^s_{\text{dom}}$ for domestic sourcing shares and $\mathbf{C}^s_{\text{low}}$, $\mathbf{C}^s_{\text{med}}$ and $\mathbf{C}^s_{\text{high}}$ for sourcing shares from, respectively, low-wage, medium-wage and high-wage countries.

Final demand ($\mathbf{y}^*$) can be split in an analogous way. It is the Hadamard product of final demand sourcing shares ($\mathbf{F}$) and total final demand by sourcing country and industry irrespective of the origin of the goods or services, which is a product of industry shares in final demand (consumption patterns) ($\mathbf{B}$) and a vector of the level of final demand (consumption level) by country ($\mathbf{y}$). Just like $\mathbf{C}$, $\mathbf{F}$ can be subdivided into $\mathbf{F}^s_{\text{dom}}$ for domestic sourcing shares and $\mathbf{F}^s_{\text{low}}$, $\mathbf{F}^s_{\text{med}}$ and $\mathbf{F}^s_{\text{high}}$ for sourcing shares from, respectively, low-wage, medium-wage and high-wage countries.

Turning to changes over time in emissions, we define a SDA[17] of our MRIO model in Equation 2 to distinguish a CO_2 emission intensity effect ($\mathbf{D}_{\text{int}}$), domestic, low-wage,

[13] For the definition of the groups of countries, see Figure 1 in the data section.
[14] For a detailed discussion of the model, see the supplementary material.
[15] The symbol $*$ stands for the sum over the index that it replaces, see the supplementary material.
[16] *C* is equivalent to the import structure matrix in Oosterhaven and Van der Linden (1997).
[17] In the SDA literature, the decomposition approach proposed in Dietzenbacher and Los (1998) has become widely used. This implies computing the average of the *k!* different complete weight decompositions, where *k* stands for the number of determinant variables. As shown in Hoekstra and van den Bergh (2003) and Hoekstra (2005), this is equivalent to computing the decomposition formula suggested in Sun (1998) that rests upon a linear growth path between two discrete points.

medium-wage and high-wage intermediate sourcing effects ($\mathbf{D}_{\text{Cdom}}$, $\mathbf{D}_{\text{Clow}}$, $\mathbf{D}_{\text{Cmed}}$ and $\mathbf{D}_{\text{Chigh}}$), a technical input structure effect ($\mathbf{D}_{\text{A}*}$), domestic, low-wage, medium-wage and high-wage final demand sourcing effects ($\mathbf{D}_{\text{Fdom}}$, $\mathbf{D}_{\text{Flow}}$, $\mathbf{D}_{\text{Fmed}}$ and $\mathbf{D}_{\text{Fhigh}}$), a final demand composition effect ($\mathbf{D}_{\text{B}}$), and a final demand volume effect ($\mathbf{D}_{\text{y}}$) (Equation 3). These effects may be grouped together in four main categories: technology, sourcing, consumption patterns and consumption growth

$$\Delta \mathbf{u} = \underbrace{\mathbf{D}_{\text{int}} + \mathbf{D}_{\text{A}*}}_{\text{Technology}} + \underbrace{\mathbf{D}_{\text{Cdom}} + \mathbf{D}_{\text{Clow}} + \mathbf{D}_{\text{Cmed}} + \mathbf{D}_{\text{Chigh}} + \mathbf{D}_{\text{Fdom}} + \mathbf{D}_{\text{Flow}} + \mathbf{D}_{\text{Fmed}} + \mathbf{D}_{\text{Fhigh}}}_{\text{Sourcing (ECS)}} + \underbrace{\mathbf{D}_{\text{B}}}_{\text{Consumption patterns}} + \underbrace{\mathbf{D}_{\text{y}}}_{\text{Consumption growth}}. \quad (3)$$

The geographic origin of intermediates, reflected in $\mathbf{C}$, contains the shares of source countries in total intermediates used by industries in sourcing countries. The column sums of $\mathbf{C}$ are equal to N for all periods and changes in $\mathbf{C}$ always sum to 0, i.e. if the share of foreign sourced inputs rises then the share of domestically sourced inputs automatically falls. Hence, splitting $\mathbf{C}$ into $\mathbf{C}_{\text{dom}}$, $\mathbf{C}_{\text{low}}$, $\mathbf{C}_{\text{med}}$ and $\mathbf{C}_{\text{high}}$ reveals the effects of compensating changes in domestic and foreign sourcing. Leaving aside the influence of the decomposition weights, the respective effects $\mathbf{D}_{\text{Cdom}}$, $\mathbf{D}_{\text{Clow}}$, $\mathbf{D}_{\text{Cmed}}$ and $\mathbf{D}_{\text{Chigh}}$ do not reflect an absolute rise or fall in emissions but rather shifts in emissions between countries due to changes in sourcing patterns. The same reasoning holds for $\mathbf{D}_{\text{Fdom}}$, $\mathbf{D}_{\text{Flow}}$, $\mathbf{D}_{\text{Fmed}}$ and $\mathbf{D}_{\text{Fhigh}}$. The total sourcing effect, i.e. the sum of the intermediate and final demand sourcing effects, is the ECS. Since changes in the $\mathbf{C}$ and $\mathbf{F}$ sum to 0, the ECS comes from differences in the weights, in particular differences in technology between source countries. A positive (negative) ECS indicates a shift in sourcing patterns towards countries with more (less) emission-intensive production technologies.

The MRIO model in Equation 2 is expressed such that, when the SDA is applied, a distinction becomes possible between effects on territorial emissions originating from changes in country r and effects originating from changes in other countries. The former are domestically induced (referred to as 'domestic effects' in the remainder of the text) and the latter foreign induced ('foreign effects'). Basically, it comes down to defining bilateral effects between country s where the change in a variable occurs and country r, for which we measure the resulting change in territorial emissions.

Here, the interpretation of the domestic and foreign effects of sourcing is of particular interest. The domestic effect of $\Delta\mathbf{C}_{\text{dom}}$ is the effect of changes in domestic sourcing of intermediates in country s on its territorial emissions, e.g. if there is less domestic sourcing in s then this will reduce territorial emissions in s. This effect also comprises second round effects for domestic producers. Basically, it measures avoided territorial emissions in s due to less domestic sourcing. However, less domestic sourcing is compensated by increased foreign sourcing, i.e. a rise in $\mathbf{C}_{\text{high}}$, $\mathbf{C}_{\text{med}}$ and $\mathbf{C}_{\text{low}}$. This will have no effect on territorial emissions in s except for second round effects. But it does affect territorial emissions in the source countries (r), i.e. it leads to a foreign effect. Take as particular example a country *r* that belongs to the group of low-wage countries. Changes in sourcing patterns in high-wage countries that consist in a shift from domestic sourcing towards sourcing from low-wage countries, in particular country *r*, will raise demand for intermediates from *r* and thereby *r*'s territorial emissions. Finally, based on the bilateral effects, it is also possible to calculate the effects of changes in variables for a particular country *s* on global emissions. They amount to the sum of the domestic effects on territorial emissions in *s* and the foreign effects on territorial emissions in all other countries.

2.2. Data

For the computation of this SDA, we use the world input–output tables (WIOTs) in current prices and previous year's prices from the WIOD. Their construction is described in Dietzenbacher et al. (2013). These are industry-by-industry WIOTs derived from supply-and-use tables. The construction of the use tables of imports relies on international trade statistics with a distinction of imports for intermediate consumption and imports for final consumption based on the Broad Economic Categories (BEC) classification. Regarding previous year's prices, we use the most recent version of the WIOTs published in December 2014 (Los et al., 2014). The WIOTs contain data on 41 countries/regions (the 27 European Union member states as of 2007 plus Australia, Brazil, Canada, China, India, Indonesia, Japan, Mexico, Russia, South Korea, Taiwan, Turkey, the United States and the rest of the world (RoW)) with an industry breakdown into 35 industries. There are five final demand categories in the WIOTs, but we only consider aggregate final demand. For our SDA, we consider 1995–2007 as the full sample period. As mentioned earlier, the restriction to 2007 as end period is to avoid that the results are influenced by the 2008 financial crisis.[18]

Our choice of using data from WIOD rather than from other MRIO databases is due to the availability of tables in previous year's prices in WIOD.[19] Having some form of constant price tables is a requirement for any SDA calculation so as to avoid that results are influenced by price changes. As emphasized in Arto and Dietzenbacher (2014), tables in previous year's prices are suited for SDA calculations for year-on-year changes in emissions. Take, e.g. changes in global CO_2-emissions between 2000 and 2001. For decomposing these changes, we use the WIOT for 2000 in current prices and the WIOT for 2001 in prices of 2000, i.e. tables that are expressed in prices of the same year. Just like the overall change, all the year-on-year effects calculated when applying our SDA are expressed in Megatons of CO_2. These year-on-year effects can then be cumulated over the full sample period.

Furthermore, data on CO_2-emissions by country and industry are drawn from WIOD's environmental satellite accounts (see Timmer, 2012). In terms of units, emissions are measured in Megatons (Mt) or Gigatons (Gt) of CO_2.

Finally, we also take employment data from the socio-economic accounts that are part of WIOD to compute hourly wage rates as labour compensation per hour worked in current US dollars. We then establish a ranking of the 41 individual countries/regions according to

[18] We have, however, also tested our SDA for the years 2007–2009 given that WIOTs are available for these years. The results found for 1995–2007 are confirmed as shown in the supplementary material Table A5, which is identical to Table 1 but covers the period 1995–2009. Note that the ECS is even higher, accounting for 29% of the rise in global emissions over this period.

[19] For a more general comparison of the various MRIO databases that have recently been developed, see Inamoto and Owen (2014). More specifically, Owen et al. (2014) compare the results of consumption-based emission accounting for three MRIO databases (Eora, GTAP and WIOD) by means of a SDA.

Figure 1. Low-wage, medium-wage and high-wage country groups according to 1995 hourly wage rates in current US dollars (in alphabetical order).

Low-wage countries (<5US$)	Medium-wage countries (>5US$, <10US$)	High-wage countries (>10US$)
Brazil	Cyprus	Australia
Bulgaria	Greece	Austria
China	Korea	Belgium
Czech Republic	Malta	Canada
Estonia	Portugal	Denmark
Hungary	Slovenia	Finland
India	Taiwan	France
Indonesia		Germany
Latvia		Ireland
Lithuania		Italy
Mexico		Japan
Poland		Luxemburg
Romania		Netherlands
Russia		Spain
Slovakia		Sweden
Turkey		United Kingdom
RoW		United States

their 1995 hourly wage rates and divide them into 3 groups defined by the threshold hourly wage rates of 5 and 10 US dollars. As shown in Figure 1, the low-wage group comprises 17 countries with wage rates below 5 US dollars in 1995, the medium-wage group comprises 7 countries with 1995 wage rates between 5 and 10 US dollars, and the high-wage group comprises 17 countries with 1995 wage rates above 10 US dollars. It is noteworthy that the ranking of these countries in terms of the hourly wage rate in current US dollars was generally stable and changes, if any, occurred only within the groups during the study period. In other words, despite the overall upward shift in wage rates, the composition of low-wage, medium-wage and high-wage country groups was identical in 1995 and 2007.[20]

3. Results

The increase in global production-related CO_2-emissions over the period 1995–2007 amounts to 6.3 Gt. As illustrated in Figure 2, most of this increase has occurred in low-wage countries, in particular China and to a lesser extent India. The small group of medium-wage countries accounts for 5% of the increase and high-wage countries for 12%. Among the latter, the main contribution comes from the US, while the contribution of the EU27 is rather limited.[21] The country distribution of the increase in global CO_2-emissions is thus skewed towards low-wage countries.

Table 1 summarizes decomposition results for global emissions and for territorial emissions in the three country groups. Effects are aggregated into four categories as specified in

[20] The threshold wage rates would then be 9.3 and 20 US dollars in 2007.

[21] Territorial production-related CO_2-emissions have fallen over 1995–2007 in ten sample countries – all of them EU27 member states (Belgium, Bulgaria, France, Germany, Hungary, Luxembourg, Latvia, Poland, Romania and Slovakia). The total decrease amounted to 89 Mt.

Figure 2. Distribution of the increase in global CO_2 emissions, 1995–2007.

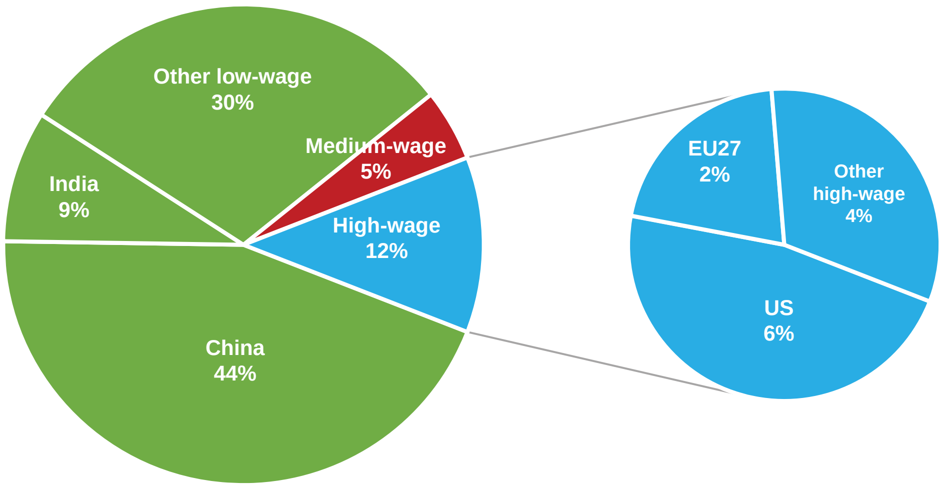

Table 1. (Colour online) Decomposition of changes in CO_2 emissions (in % of global change) between 1995 and 2007 with four major groups of effects.

	Technology (%)	Sourcing (%)	Consumption patterns (%)	Consumption level (%)	Total (%)
High-wage	−26	−8	−7	53	12
Medium-wage	−2	1	1	6	5
Low-wage	−62	25	6	114	83
Total	−90	18	−1	172	100

Equation 3: technology, sourcing, consumption patterns and consumption level. All results in the table are expressed in per cent of the global change in emissions over 1995–2007. The bottom row shows decomposition results for global emissions. The rows above contain decomposition results for changes in territorial emissions in each of the three country groups. The shares reported in the last column of the table correspond to the shares of the country groups in the change in global emissions that have been illustrated in Figure 2.

The consumption level and technology effects (positive and negative, respectively) dominate the increase in global CO_2- emissions. Changes in consumption patterns play only a minor role. These results are in line with those reported in Arto and Dietzenbacher (2014). The ECS amounts to 18% of the increase in global CO_2-emissions or over 1100 Mt of CO_2 over the period 1995–2007.[22]

It reveals to what extent technological differences in the production of sourced goods and services contribute to the rise in global emissions. The ECS would be equal to zero in a world where intermediate and final goods and services are produced with identical technologies everywhere. Thus, the observed effect results from a shift in sourcing to countries with more emission-intensive technologies. When US industries source intermediates from China which they used to source domestically, there is a net increase in global CO_2-emissions, not only because the goods are now shipped over a probably much

[22] As mentioned earlier, we have also done the decomposition calculations for the period 1995–2009. The ECS is as high as 29% (see supplementary material Table A5). However, given the economic crisis during the years 2008–2009, we prefer to focus on the results for 1995–2007.

longer distance leading to emissions from transportation but also because production technologies of Chinese suppliers are more emission-intensive than those of US suppliers. In general, therefore, sourcing from low-wage countries that have higher CO_2-emissions per unit of output rather than from high-wage countries that have low CO_2-intensities leads to a net increase in global CO_2-emissions. The total net effect is the ECS.

The detailed decomposition results show the effect of changes in the variables of one region on the changes in global CO_2-emissions. These results are summarized in Figure 3 with a particular focus on the effect of changes in sourcing patterns of each region. Full results are provided in Tables A4(a)–(c) in the supplementary material. They also contain the effects on changes in territorial CO_2-emissions in the three wage groups, i.e. high-wage, medium-wage and low-wage countries.

According to the results in Figure 3, changes in high-wage, medium-wage and low-wage countries contribute respectively 2.4, 0.2 and 3.7 Gt to the overall increase in global CO_2-emissions between 1995 and 2007. As reported in Table A4(a), most of the additional 2.4 Gt of CO_2 emitted due to changes in high-wage countries is actually emitted in low-wage countries (2.1 Gt). High-wage countries are the only region that matters in terms of contribution to the ECS. It amounts to 1144 Mt and the global effect of changes in sourcing patterns of high-wage countries is 1074 Mt. This is the result of offsetting effects in terms of territorial emissions, i.e. a shift of the burden of emission growth. Figure 3 highlights that changing sourcing patterns in high-wage countries raise emissions in low-wage and medium-wage countries by 1.5 and 0.07 Gt, respectively, while reducing emissions in high-wage countries by only 0.5 Gt. Moreover, Figure 3 also reveals that the effect of changing sourcing patterns of low-wage and medium-wage countries on global emissions is small. Overall, it illustrates that the burden shift from higher wage to lower wage regions exceeds by far the burden shift from lower wage to higher wage regions.

Furthermore, the result for the ECS hides offsetting sourcing effects on territorial emissions for the three country groups. Changes in sourcing patterns lower territorial CO_2-emissions in high-wage countries by 8% of the global change in emissions, but raise territorial CO_2-emissions in medium-wage and low-wage countries by, respectively, 1% and 25% of the global change in emissions (see Table 1). This is illustrated on an annual basis in Figure 4. The effect of changing sourcing patterns on territorial emissions in the three country groups sum to the ECS for each year from 1996 to 2007. The cumulated ECS is depicted by the dark blue line. In all years except 1996, territorial emissions of low-wage countries rise due to changes in international sourcing patterns. The opposite holds for high-wage countries for the years 1997–2006, while the change in territorial emissions of medium-wage countries is always of minor magnitude. The rise in territorial emissions of low-wage countries exceeds by far the fall in territorial emissions of high-wage countries. Hence, the sign of the ECS is positive for all years except 1996, i.e. changing sourcing patterns foster global CO_2-emission growth.

Table 2 shows more detailed decomposition results for changes in territorial emissions in the three regions (high-wage, medium-wage and low-wage countries). Changes and effects are reported in Mt of CO_2. The full results with a split according to where the changes occur are provided in Tables A3(a)–(c) in the supplementary material.

For high-wage countries, territorial emissions have risen by 747 Mt between 1995 and 2007. The decomposition results reveal the following profile: the very substantial increase in CO_2-emissions due to consumption growth (3317 Mt) is partially compensated by the

Figure 3. (Colour online) Changes in global CO_2-emissions due to changes in variables in high-wage, medium-wage and low-wage countries and the sourcing effect, 1995–2007.

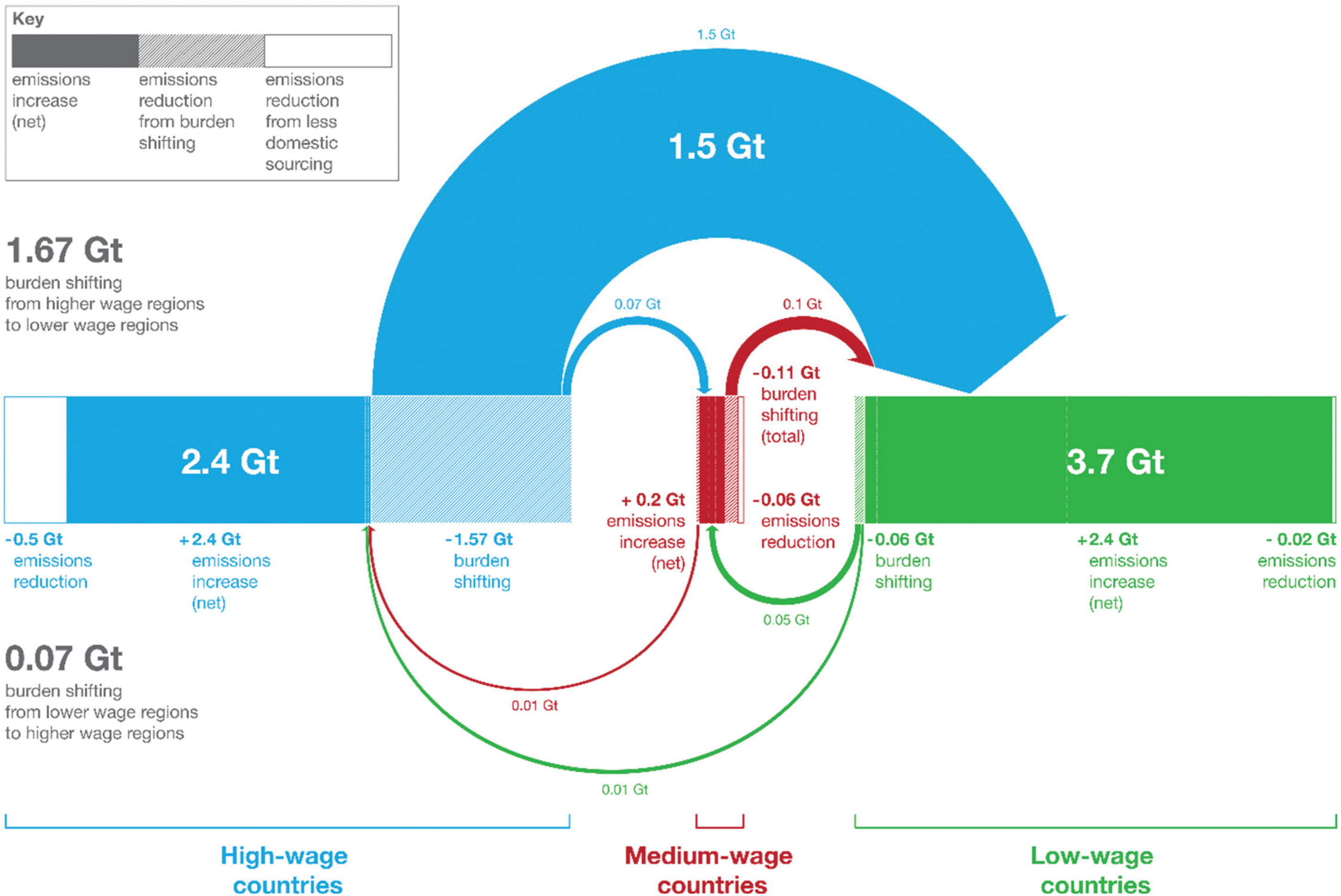

Figure 4. (Colour online) The effect of changing sourcing patterns in terms of additional territorial CO_2-emissions by region and the ECS in Mt of CO_2, 1995–2007.

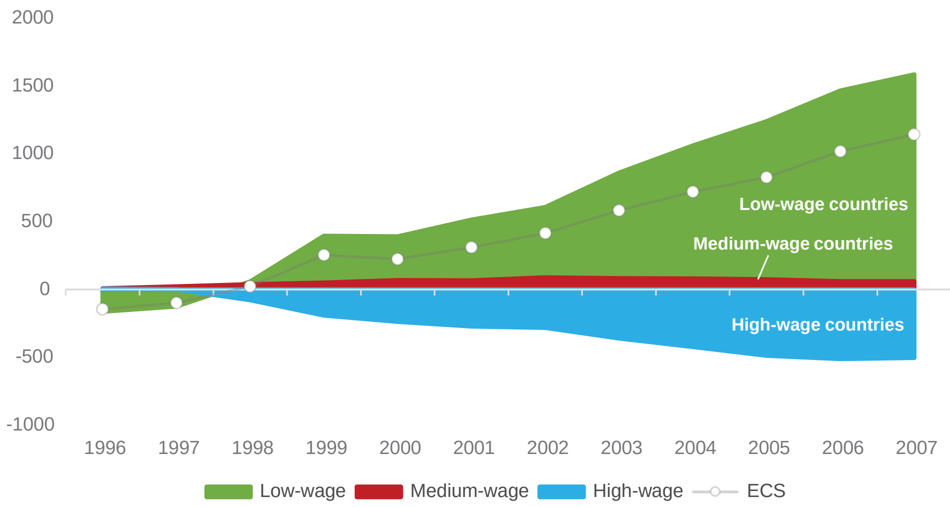

Table 2. Decomposition of changes in territorial CO_2-emissions (in Mt) of high-wage, medium-wage and low-wage countries between 1995 and 2007.

	Δvar	High wage	Medium wage	Low wage
Technology	**v**	−1018	−286	−5851
	A	−625	140	1957
Sourcing	$\mathbf{C}_{dom}$	−472	−44	−810
	$\mathbf{C}_{low}$	71	20	1523
	$\mathbf{C}_{med}$	13	90	35
	$\mathbf{C}_{high}$	80	−1	44
	$\mathbf{F}_{dom}$	−332	−44	−350
	$\mathbf{F}_{low}$	61	22	1109
	$\mathbf{F}_{med}$	4	17	6
	$\mathbf{F}_{high}$	74	0	28
Consumption	**B**	−425	38	354
	y	3317	353	7218
Total		747	305	5263
Total sourcing		−502	61	1584

effects of emission intensities (−1018 Mt), the technological input structure (−625 Mt) and final demand composition (−425 Mt). The total sourcing effect for high-wage countries amounts to a reduction of 502 Mt of CO_2. In other words, without this shift in emissions through increased foreign sourcing, the rise in territorial CO_2-emissions in high-wage countries would have been nearly 70% higher. The sourcing effect of intermediates is slightly higher than the effect of final goods and services (−472 and −332 Mt for sourcing of intermediate and final demand, respectively). The latter two effects are essentially driven by the effect of less domestic sourcing in high-wage countries, i.e. the domestic effect (respectively −482 and −276 Mt, see Table A3(a) in the supplementary material). Foreign effects of sourcing turn out to be less important.

The territorial CO_2-emissions of the small group of medium-wage countries has increased by 305 Mt over the period 1995–2007. The large positive final demand level effect

(353 Mt) is partially compensated by lower emission intensities (−286 Mt). The total sourcing effect amounts to an increase of 61 Mt of CO_2. It is mainly due to a rise in emissions due to increased sourcing from these medium-wage countries by both high-wage and low-wage countries (see Table A3(b) in the supplementary material). This increase offsets the reduction in emissions due to cutbacks in domestic sourcing by industries in medium-wage countries.

More than 80% of the rise in global CO_2-emissions over 1995–2007 occurs in low-wage countries. The detailed decomposition results for countries in this group in Table A3 (in the supplementary material) show that the increase in their territorial emissions due to consumption growth (7218 Mt) is to a large extent offset by the effect of lower emission intensities (−5851 Mt). However, the effects on territorial emissions of the technological input structure (1957 Mt), sourcing (1584 Mt) and to a lesser extent the final demand composition (354 Mt) lead to a substantial overall increase. The sourcing effect amounts to 30% of the total rise in emissions in low-wage countries. The details of the sourcing effect in Table A3(c) in the supplementary material reveal that, for both intermediate and final demand, increasing sourcing from low-wage countries, in particular by high-wage countries, contributes significantly to the increase in emissions in low-wage countries (respectively, 832 and 775 Mt for intermediate and final goods and services).

4. Conclusions and policy implications

Developments in information and communication technologies have facilitated the reorganization of production activities in global value chains. Although the main underlying driver for this reorganization are wage cost differentials rather than differences in environmental regulations and compliance costs, the changes in sourcing patterns prompted by this reorganization have important consequences for the geographic distribution of global CO_2-emissions growth. In particular, high-wage countries increasingly source goods and services from low-wage countries rather than domestically or from other high-wage countries. Our results for the years 1995–2007 show that this has reduced territorial CO_2-emissions growth in high-wage countries by almost 500 Mt but increased territorial CO_2-emissions growth in low-wage countries by more than 1500 Mt. As a consequence, the emission cost of international sourcing (ECS) amounts to about 1100 Mt of CO_2 or 18% of the overall increase in CO_2 emissions. The ECS arises mainly due to differences in CO_2-emission intensities between the two groups. With identical emission intensities in all countries, changing sourcing patterns would be neutral with respect to global CO_2-emissions.

The recent Intergovernmental Panel on Climate Change report emphasizes that without a dramatic and immediate cut of GHG emissions, especially fossil fuel CO_2, keeping the global temperature increase below 2°C is infeasible. International climate change negotiations are underway to try to meet this target. The negotiations are based on the premise that territorial targets will be set for developed countries. However, the results of our analysis challenge this approach to mitigating CO_2-emission growth. As long as wage differences continue to drive emission-efficient high-wage countries to increasingly source from emission-intensive low-wage countries, the ECS will continue to rise. In other words, without substantially reducing CO_2-emission intensities in low-wage countries, wage cost-driven international sourcing will contribute to CO_2-emission growth. Despite major improvements over the years, CO_2-emission intensities of low-wage countries (median 0.30 kg CO_2/$) were still significantly higher than those of high-wage countries (median 0.10 kg CO_2/$) at the end of the period under consideration in our calculations. More recent data (IEA, 2013) confirm that the difference persists. It is largely due to differences in the fuel mix and energy efficiency: low-wage countries rely predominantly on fossil fuels, especially carbon intensive coal. In addition, there are major efficiency gaps between the underlying energy infrastructures of the two groups. Japanese fossil fuel-based power plants, e.g. enjoy about 43% thermal efficiency, while those in China and India report, respectively, 32% and 28% thermal efficiencies (IEA, 2008). Given the longevity of industrial and energy infrastructure and little or no change in favour of low-carbon energy sources, the trend in the ECS is expected to persist, thereby challenging international climate change mitigation efforts.

Introducing carbon taxes and tradable emission permits is considered as a policy instrument for fostering the development and adoption of low-carbon technologies and production processes. However, such a policy implemented by a subset of the countries of the global economy is likely to give rise to carbon leakage by creating an incentive to relocate emission-intensive production stages to or to source emission-intensive intermediate inputs from the countries that fail to apply these instruments. By the same token, carbon taxes and tradable emission permits implemented by a subset of the countries are not only politically unpalatable but also likely to exacerbate the ECS by altering sourcing patterns such that more intermediates are imported from the countries where production processes are more emission-intensive.

Free allowance allocation has been the dominant policy approach to tackle the tax-induced carbon leakage. But since free allowance allocation jeopardizes the original emission reduction goal of the carbon tax, it has been suggested to introduce complementary instruments, e.g. border tax adjustment (BTA) (Ismer and Neuhoff, 2007) or carbon pricing mechanisms that combine free allowance allocation with a consumption charge for selected carbon intensive materials (Neuhoff et al., 2015). However, it may be questioned whether the use of these complementary instruments is really warranted, given that the empirical evidences do not support significant 'strong' carbon leakage despite substantial differences in the stringency of climate policy between countries. Furthermore, the trade flows that may lead to 'weak' carbon leakage are mainly driven by factor prices, in particular wages rather than the carbon price at its current level. The same holds for the ECS. As we have emphasized in this work, the changes in sourcing patterns underlying the ECS occur in response to factor price differences rather than carbon price differences. Therefore, it seems unlikely that policy instruments such as BTA will allow to reduce the ECS substantially.

Instead, our analysis and results call for an alternative strategy to cope with the consequences in terms of emissions of increasing wage cost-driven international sourcing: reducing the carbon intensity of the energy infrastructure in low-wage countries through, e.g. the Clean Development Mechanism (CDM) (Dechezleprêtre et al., 2008; Popp, 2011). While some CDM projects have been reported to achieve only a limited success (Sutter and Parreño 2007; Subbarao and Lloyd, 2011), CDM can, when properly implemented, potentially deliver both an emission reduction and a transfer of low-carbon technologies to low-wage countries. Other mechanisms for low-carbon technology transfer to low-wage countries should also be actively pursued. In this context, it would be crucial to resolve the remaining issues such as the safeguard of intellectual property rights around low-carbon technologies and ensuring mutual benefits for all parties involved (Ockwell et al., 2008; 2010; Popp, 2011). Indeed, our results show that the transfer of low-carbon technology to low-wage countries would not only lower emissions due to the rise in their domestic consumption but also reduce the additional emissions due to the ECS by narrowing the technology gap.

Disclosure statement

No potential conflict of interest was reported by the authors.

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