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Functional Specialization in Global Supply Chains and the Environmental Performance of Countries

Bart Los and Xianjia Ye

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university of groningen
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Bart Los and Xianjia Ye

(University of Groningen, Faculty of Economics and Business, Groningen Growth and Development Centre)

Short Abstract

The rapid proliferation of Global Supply Chains (GSCs) has led to a kind of trade specialization that goes beyond specialization in industries. Countries now specialize in performing business functions, which makes fair comparisons of the performance of industries across countries complicated. One of such comparisons relate to their environmental performance. In this paper, input-output techniques and regression analyses are used to find relationships between the types of business function into which countries and industries therein have specialized and their CO_2 emissions per dollar of value added. The analyses relate to the period 1999-2008, when GSCs became pervasive. The data are for 40 countries and 34 industries. The input-output tables and emission data are taken from the World Input-Output Database and the business function data from Timmer, Miroudot and De Vries (*Journal of Economic Geography*, 2019). We provide accounts of the extent to which trade-induced specialization in functions affect the emission performance of countries.

Keywords: functional specialization; international trade; CO2 emissions; input-output analysis

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1. Introduction

By now, there is a widespread consensus that drastic reductions in greenhouse gas emissions are needed to avoid an excessive rise of temperatures and its dramatic consequences for substantial parts of the global population. Given that the monetary costs of the required rapid transition can be high (at least in the short run), international negotiations regarding emission reductions by countries tend to be cumbersome. The major climate summits over the past decades were marred by disagreements about how much each country should contribute to the global objective. The increasing interdependence among countries in the world has made discussions about a 'fair distribution of the burden' cumbersome. International trade implies that the location of production (and emissions) differs from the location of consumption. The global trade intensity (e.g. measured as the ratio between world trade and world GDP) has been increasing over time, causing a continuing divergence between national emissions measured from the perspective of 'producer responsibility' and from the viewpoint of 'consumer responsibility'. Loosely described: Country A might emit lots of greenhouse gases in producing products that are not only consumed domestically by A, but also by Country B. Country A's environmental performance is thus affected negatively by trade with Country B (see, e.g., Peters and Hertwich, 2008; Davis and Caldeira, 2010).

In this paper, we tackle the question "to what extent did international trade contribute to differences in CO_2 intensities across countries in the 1999-2008 period?". In a broad sense, this is not a very new question. We argue, however, that the nature of trade changed in the decade preceding the global crisis in such a way that existing methodologies using input-output analysis (see, e.g. Serrano and Dietzenbacher, 2010; Arto and Dietzenbacher, 2014; Wiedmann et al., 2015) to address questions like these might no longer yield meaningful answers. The information and communication revolution has allowed firms that govern GSCs to relocate specific business functions *within* industries to places in different countries (see, e.g., Grossman and Rossi-Hansberg, 2008; Timmer et al., 2019), following the well-known logic of comparative advantage. Some of these functions tend to be less polluting than others (fabrication activities tends to be 'dirtier' than other activities, such as R&D, as we will show empirically). Hence, restricting the analysis of the effects of trade on environmental performance to issues related to specialization in industries (without devoting attention to functional specialization within industries) might well sketch misleading pictures.

We propose a novel empirical approach to address this problem and examine the size of the differences with the more traditional approach that focuses on industry specialization alone. We use the 2008 world input-output table and CO_2 emissions data from the 2013-release of WIOD (Timmer et al., 2015) and compatible data on the functional mix of the labor forces of 35 industries in 40 countries (Timmer et al., 2019) to address three (related) questions:

- To what extent can between-country differences in CO_2 emissions by a given industry be attributed to between-country differences in the functional mixes in that industry?
- Which parts of differences in the environmental performance of countries (measured by CO_2 emissions per dollar of GDP) in 2008 can be attributed to international trade, when taking functional specialization due to the proliferation of GSCs into consideration?

Addressing these questions requires the development of some novel indicators rooted in input-output analysis and the use of regression analysis.

The first question will be addressed by regression analysis. We will regress CO_2 emissions per dollar of value added in a given industry on the shares of the broad business functions fabrication in value added in the industry considered, in a cross-sectional set-up. We also consider indirect effects: Relative to other functions, fabrication activities do generally not just lead to more emissions in the industry itself, but also require more electricity or other types of intermediate inputs. The production of these also cause emissions. Using variants of an approach suggested by Los et al. (2016), indicators that take such indirect effects into account will be constructed and regressed on the value added shares of fabrication in exporting industries.

We approach the second question by adopting an accounting framework. We consider differences in emissions intensities of countries vis-à-vis the global average as the sum of three terms: differences in trade-induced industry specialization, differences in trade-induced functional specialization and a residual, which we call "country-specific differences". Since we are primarily interested in the effects of trade, we do not dig deeper into these differences, but is probably safe to argue that these are largely determined by energy-mix differences between the country considered and the global average. We define industry-specific average global technologies by means of world input-output tables, regression coefficients obtained in addressing the first question and data on the functional mix of industries in countries.

Our analysis is related to the literature on the Environmental Kuznets Curve (EKC), which posits that the relationship between GDP per capita of countries and their emission intensity can be described by an inverted U-shape. The 'environmental optimism' associated with the EKC (if economic progress continues, emission intensities will decline) was dampened by findings that advanced countries tended to reduce their territorial emission intensities by offshoring the production of emission-intensive products. Hence, empirical support for the existence of the EKC is weaker if consumer-based responsibility is considered, rather than producer-based responsibility. Our findings suggest that this difference is to some extent due to functional specialization induced by trade.

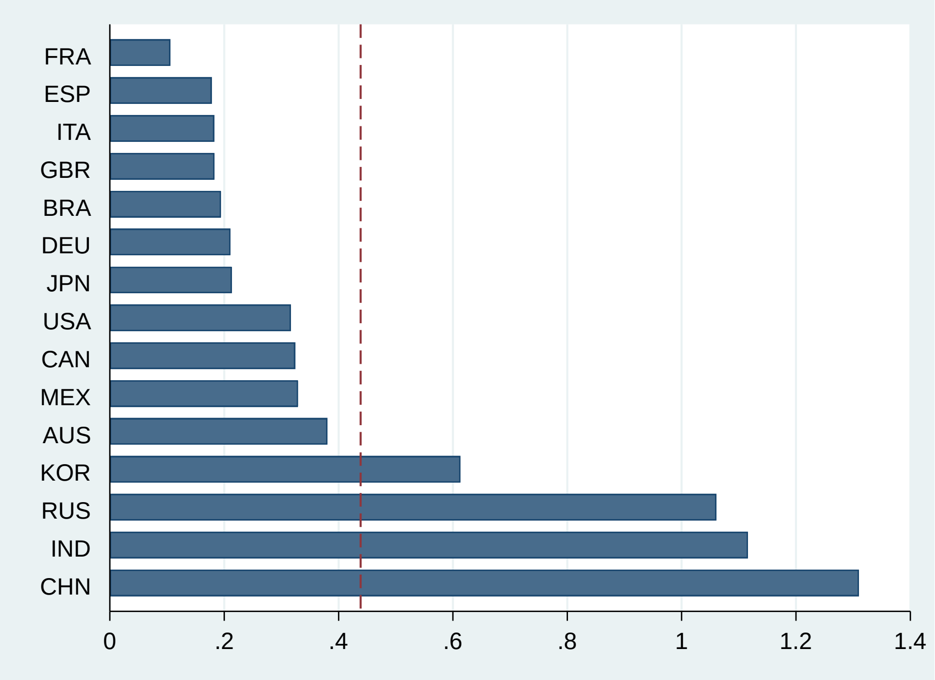
The structure of the rest of the paper is as follows. Section 2 provides the context of the ideas behind the analysis and includes some informative background figures. Section 3 then provides answers to the first of the questions listed above. Section 4 is devoted to addressing the second question and Section 5 to the last one. Section 6 concludes, by discussing the broader implications of the findings.

2. Background and Related Literature

2.1 National emission performance and trade-induced industrial specialization

Substantially reducing greenhouse gas emissions is essential for keeping global temperatures within ranges that are manageable in large parts of the world, as has been argued since long in IPCC reports. Still, multilateral negotiations to achieve have proven difficult. In the short run, adjusting the level and/or structure of economic activity in countries is costly. Hence, agreeing on the way in which to share the global burden of adjustment is tough and countries tend to put forward accounting procedures that minimize the part of the problem they have to address. As is well-known by now, the increased interconnectedness of industries in countries in different parts of the world and the increasing trade in final products have given rise to several perspectives on which country is responsible for which part of the emissions.[1]

Figure 1: Economy-wide industrial CO_2 emissions (in kilotons per million dollar) of GDP, 15 largest economies, 2008



Note: Kilotons per million dollar of value added; FRA: France; ITA: Italy; UK: United Kingdom; ESP: Spain; BRA: Brazil; JPN: Japan; GER: Germany; USA: United States; CAN: Canada; MEX: Mexico; AUS: Australia; KOR: South Korea RUS: Russia; IND: India; CHN: China. The dashed vertical line indicates the global emission intensity.

Source: Authors' computations based on the World Input-Output Database, 2013 release (Timmer et al., 2015).

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[1] In this paper, we restrict our analysis to emissions of carbon dioxide. The analytical framework that we propose could be used to study the relation between other types of pollution and environmental degradation in a similar way.

Figure 1 presents the CO_2 emission intensities of the fifteen largest economies (measured in terms of GDP) in 2008, according to the 2013-release of the World Input-Output Database (WIOD, see Dietzenbacher et al., 2013; Timmer et al., 2015).[2] France and Italy appear as the cleanest countries in this respect, with emission intensities below 0.2 kilotons per million dollar of GDP. At the other end of the spectrum, we find countries like Russia, India and China, which all emit more than 1.0 kilotons per million dollars of GDP. Just considering this group of fifteen large economies shows that the variation around the global emission intensity of 0.44 kt/$.

The question what factors are driving differences in CO_2 intensities across countries has attracted a lot attention, both among academics and policymakers. In a world without trade, answers would have been more straightforward than in the real world: Countries like China and Russia would have to reduce their emission intensities more than France and Japan.[3] Producer responsibility and consumer responsibility would coincide. In reality, however, international trade has become an increasingly important phenomenon in the world economy. This has led to at least three related bodies of literature.

First, studies quantifying the differences between the producer responsibilities and consumer responsibilities of countries gained in importance, in particular after intercountry input-output tables became available, about ten years ago (see Tukker and Dietzenbacher, 2013, for an early overview, and Rahman et al., 2022, for an empirical comparison). These studies (see e.g., Wilting and Vringer, 2009) find that the consumer responsibility of advanced countries tends to be higher than their producer responsibility, while the opposite is found for many emerging countries. These differences are even more pronounced for those advanced countries that have a substantial trade deficit (the United States is the prime example) and those emerging countries that have a substantial trade surplus (such as China).

Second, several studies have linked the literature on the Environmental Kuznets Curve (EKC) to international trade. Although the evidence is mixed, some studies found evidence of an inverted U-shape relationship between emission intensity and GDP per capita. When countries grow richer, they first tend to become more polluting, up until a GDP per capita level after which emission intensities start to decline. This phenomenon (which might give reason for some optimism) has often been attributed to the emergence of opportunities to invest in cleaner technologies and to a shift in consumption from ‘dirty’ manufactured products to ‘clean’ services associated with increasing standards of living (see, e.g., Stern, 2004, for a critical overview of the literature). These explanations relate to drivers that could explain the EKC if countries would be closed economies. If trade is taken into consideration, the low emission intensities of advanced countries could be due to the ‘offshoring’ of pollution-intensive industries to poorer countries. This phenomenon might also be responsible

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[2] The figure only includes CO_2 emissions in industries. Emissions by households have been excluded in Figure 1 and will not be considered in our analysis. In our analysis, we focus on 2008 because this is the most recent year for which the required data on the functional employment mixes of industries are currently available. These data are currently only compatible with the industry classification of the 2013-release of WIOD, which is the reason that we do not use the 2016-release of this database.

[3] Such a view would disregard (important) issues related to differences between contributions to current worldwide emissions (flows) and to the stocks of CO2 in the atmosphere, which have been determined by contributions to flows in the past few decades. In this paper, we focus on emissions in 2008 only.

for the high emission intensities of emerging countries. Including the industry composition of imports and exports in regression analyses that quantify the effects of potential determinants on emission intensities generally do not yield substantial impacts of trade (see, e.g. Cole, 2004). The link with the difference between producer responsibility and consumer responsibility for emissions as discussed above is evident, but the conclusions are different. In computing consumer responsibility, usually the actual production and emission technologies at industry level are considered (which often vary considerably across countries), while studies focusing on trade as a potential determinant of EKC-findings often consider the role of net trade in products, implicitly assuming that each of these is produced according to the same technology across countries.

Finally, our analysis is closely linked to studies into the pollution haven hypothesis (PHH). Traditional trade theories argue that differences in technology and/or the relative availability of production factors yield specialization into specific industries, according to the logic of comparative advantage. The PHH (see e.g. Grossman and Krueger, 1993; Copeland and Taylor, 2003; Eskeland and Harrison, 2003; Levinson and Taylor, 2008) basically argues that emissions can be seen as a priced production factor, similar to labor and capital. Differences across countries in the strictness of environmental regulation cause differences in the relative price of emissions, thereby giving countries without strict regulation a comparative advantage in emission-intensive industries. Given that poorer countries tend to have weaker environmental regulations, polluting production activities should thus tend to be located in poorer countries. In general, tests of the PHH using macroeconomic data is that empirical support is weak, if not nonexistent (see, e.g. Shapiro and Walker, 2018, for a quantitative explanation of the decline in emissions by the US manufacturing sector). At the same time, microeconomic analyses frequently yielded evidence that is compatible with PHH.[4]

Several studies have come up with potential explanations for these somewhat paradoxical results. Ederington et al. (2005), for example, argue that pollution haven effects might be observed in industries that are more footloose (i.e., offshoring is cheaper or less complicated) and between specific pairs of different countries (while most trade tales place between similar countries).[5] Antweiler et al. (2001) argue that pollution-intensive industries also tend to be relatively capital-intensive. The comparative advantages emanating from these two production factors run into opposite directions. If the price of emissions is not high enough in advanced countries, the effect of differences in the price of capital might be the dominating driver of trade patterns.[6]

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[4] See, e.g. Becker and Henderson (2000) for an early plant-level study for the US. Hering and Poncet (2014) found effects of differences in the strictness of city-level restrictions to reduce sulfur dioxide emissions across Chinese cities on the composition of their exports. Bombardini and Li’s (2020) findings for Chinese prefectures and Barrows and Ollivier’s (2021) findings for Indian manufacturing firms are also in line with PHH.

[5] See also Cole et al. (2010).

[6] This is an important reason why the European Commission is thinking about complementing its policies to increase the price of carbon emission permits with import tariffs on ‘dirty’ products. This Carbon Border Adjustment Mechanism should avoid situations in which pollution haven effects become more important if international differences in the prices of emissions across countries increase.

In their relatively recent overview on analyses of the relationships between trade and the environment, Cherniwchan et al. (2017) argue that the weak evidence for PHH and sizable trade effects affecting EKC-findings is due to within-industry heterogeneity. If trade becomes cheaper, countries might specialize in exports by clean firms, while others might mainly export output of dirty firms in the same industry. Macroeconomic analyses tend to attribute such differences to differences in technology, while trade is actually the culprit. Cherniwchan et al. develop a simple Melitz-type theoretical model (in which firms in an industry differ in their productivity levels) to provide an analytical framework that yields testable hypotheses. Our analysis has a similar flavor. We do not focus on within-industry heterogeneity in terms of productivity, but in terms of business functions. In the next subsection, we will argue that the rapidly increasing organization of production processes in global value chains (in which functions are not necessarily co-located anymore) implied within-industry specialization in business functions, with varying degrees of 'dirtiness'.

2.2 The Global Supply Chain revolution: Functional specialization

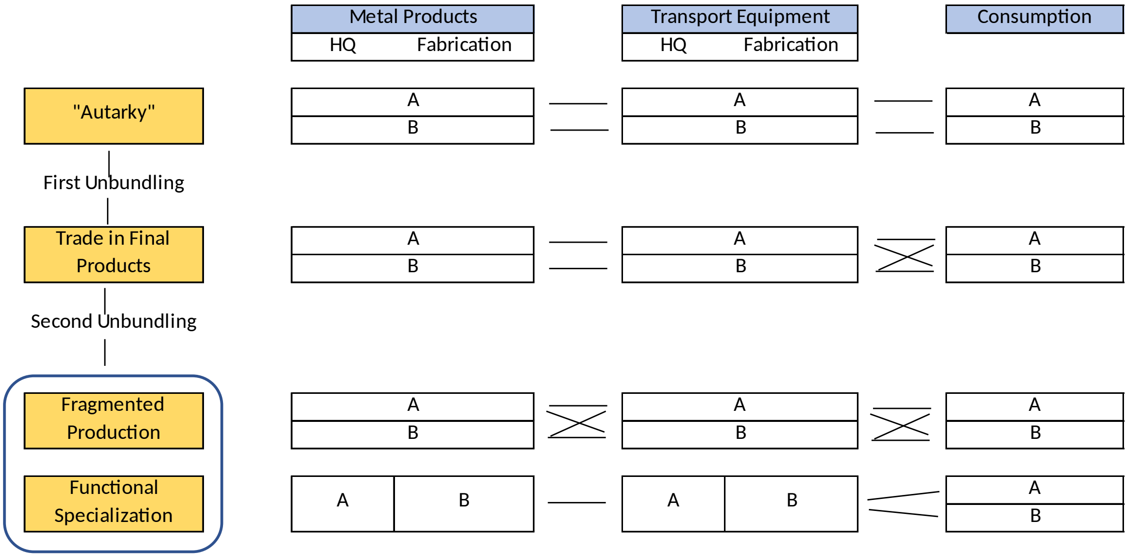
In decisions about where to locate activities, firms generally take four broad types of costs into account (Baldwin, 2016): production costs (including costs associated with polluting), tariff and non-tariff trade barrier costs, transportation costs and coordination costs. Due to a long period of trade liberalization, the costs associated with tariff and non-tariff trade barriers have declined. Transportation costs have also declined over the long run, a tendency to which containerization of international transport has contributed significantly. These two types of cost reductions played a role already in the 'first unbundling', which allowed for situations in which differences in production costs were large enough to make it worthwhile to locate *entire production processes* in one part of the world, while the main consumer markets to be served were located elsewhere (Baldwin, 2016).

For a long time, coordination costs prevented firms from locating *specific parts* of their production activities overseas. This changed with the massive innovations in information and communication technology in the 1990s and 2000s, which allowed for managing inventories from everywhere in the world, for fast and efficient transfer of product specification and rapid communication between staff. Sometimes firms decided to set up businesses in other countries and continents, in other situations the production processes of parts and components or business services were offshored to other firms elsewhere in the world. In both cases, international trade in intermediate inputs increased. The same happened to trade in final products, because it often proved profitable to locate the assembly of final products in a limited number of locations (benefiting from low production costs and economies of scale), even though customers were spread over the world (Gereffi and Fernandez-Stark, 2016). Given these two increases in trade, Baldwin's 'second unbundling' led to even more industrial specialization, since firms could use comparative advantages to a larger extent. These comparative advantages are determined by differences in the remaining cost category, production costs.

With the notable exception of Timmer et al. (2019), macroeconomic analyses have neglected a second important aspect of the second unbundling, functional specialization. The decline in coordination costs meant that firms could not only relocate parts that are representative of the activity mix of their industry to other places, but that they could also actually choose specific places for specific activities. In his discussion of the famous smile curve, Mudambi (2008), for example, argues that production processes tend to consist of activities as diverse as basic and applied R&D, design, commercialization, manufacturing, production of standardized services, marketing, advertising and brand management, specialized logistics and aftersales services, which no longer have to be co-located. If e.g. many West-European firms in a given industry decided to relocate much of their fabrication activities to Eastern European countries or to China while maintaining their R&D and marketing departments in Western Europe, functional specialization *within* industries is taking place. The second unbundling can thus be characterized as a process in which two types of specialization reshaped the global production structure simultaneously: industrial specialization (mainly in the production of intermediate inputs, reflected in internationally fragmented production processes) and functional specialization.

Figure 2 illustrates the key elements of the first and second unbundlings in a schematic way.

Figure 2: Stylized representation of trade before and after the two 'unbundlings'



Note: A and B. indicate countries Before the first unbundling, industries only sold to domestic customers, irrespective of whether these were other industries or final users. After the first unbundling, final products could be traded internationally, but intermediate inputs were almost exclusively traded on domestic markets. After the second unbundling, two changes occurred simultaneously. First, trade in intermediate inputs became an important phenomenon ('Fragmented production'), and second, functions (indicated by HQ and Fabrication) were no longer necessarily remained co-located within countries ('Functional specialization').

An (in our view often neglected) implication of functional specialization is that comparisons of the performance of industries across countries have become less meaningful after the second unbundling. How can we meaningfully compare the emission intensity in Country A's transport equipment industry to that of the same industry in Country B, if the industry in

Country A has specialized in R&D and marketing, while Country B's industry is responsible for fabrication activities? Industry labels have lost substantial parts of their importance, due to within-industry heterogeneity that goes deeper than the productivity differences stressed by Cherniwchan et al. (2017) in discussing reasons why the relation between trade-induced industry specialization and the environmental performance of countries is often found to be weak.

The fragmentation of production processes also imply that large fractions of CO_2 emissions associated with trade do not take place in the production processes of exporting industries themselves, but in supplying industries (like the power generation industry). In view of this, it is not surprising that input-output analysis in particular has contributed substantially to the analysis of the link between trade and national emissions, given its distinctive focus on interindustry linkages regarding the supply and use of intermediate inputs. Using input-output analysis, many different concepts and indicators have been developed to study various dimensions of this nexus, see e.g. Davis and Caldeira (2010), Peters et al. (2011) and López et al. (2013). Our approach is mainly related to Dietzenbacher and Mukhopadhyay (2007), who studied whether the trade pattern of India was compatible with the PHH. Like most other macroeconomic studies, they did not find evidence that India's export bundle was dirtier than its imports bundle. Data limitations made it necessary to assume that Indian imports were produced using Indian production and emission technologies. In our analysis, we have the opportunity to use world input-output tables to define global technologies. The most important difference, however, is that we consider within-industry heterogeneity, along the lines of functional specialization.

2.3 Differences in national emission intensities due to specialization

Our analysis should be seen as an accounting approach in the spirit of Grossman and Krueger (1993). We argue that differences between national emission intensities and the global average emission intensity as depicted in Figure 1 can be viewed as the sum of three terms:

1) Differences due to trade-induced industry specialization
2) Differences due to trade-induced functional specialization
3) Differences due to country-specific factors

As discussed above, in most assessments of the impact of trade on national emission performance, net trade levels for products (i.e., outputs of industries) are considered. If a country has specialized in exporting by dirty industries, it has (everything else equal) an emission intensity that exceeds the global average. Hence, the residual difference represents the sum of 2) and 3). Against the background of the discussion above, our analysis aims at quantifying the effects of both types of trade-induced specialization, which implies that the residual represents arriving a more accurate measure of 3). The most important determinants of 3) are differences in (i) the industry composition of the economy due to different compositions of final demand and (ii) industrial production technologies that differ from the 'average' technologies operated in the world. This includes, for example, the extent to which electricity is generated from non-fossil energy sources. These are differences for which countries can be held responsible, rather than the ever more intricate ways in which trade links the industries of countries with each other and with final users. Our analysis does not quantify the contributions of determinants like (i) and (ii) to country-specific differences but focuses on the quantification of the effects of international trade.

3. Quantifying the Relationship between Functional Specialization and Emissions

In this section, we analyze the extent to which within-industry differences in the functional composition of value added affect the emission intensities of an industry across countries. If these effects would appear small, it is unlikely that properly accounting for term 2) in the accounting framework discussed in the previous section would make much of a difference in empirical terms.

For each industry (for example, the “transport equipment manufacturing” industry), the regression equation from which we depart has the form

$$CO2_i = \beta_1 FVA_i + \beta_2 HQVA_i + \varepsilon_i \qquad (1)$$

The samples are cross-sections, consisting of the industry considered in each of the countries i (i=1, …, n). The variable $CO2$ indicates the carbon dioxide emissions of the industry considered.[7] FVA stands for the value added of the industry that can be attributed to the business function ‘fabrication’, while $HQVA$ indicates the value added of this industry contributed by what we will call ‘headquarters’ business functions. As will be explained in more detail in the subsection on data, fabrication value added and headquarters value added are the only value added components: $VA = FVA + HQVA$. Note that Eq. (1) does not include an intercept. This reflects the fact that we assume that emissions are zero if an industry does not generate any value added. The coefficients β_1 and β_2 are the emissions associated with adding a dollar of fabrication value added and headquarter functions value added, respectively. We assume that these marginal emissions are not related to the scale of the industry in a country.

Since we are interested in drivers of emission intensities, we divide both sides of Eq. (1) by VA_i:

$$CO2\int ¿_i = \beta_1 FVAS_i + \beta_2 HQVAS_i + u_i ¿ \qquad (2)$$

$FVAS$ and $HQVAS$ stand for the fabrication’s value added share and the headquarters’ value added share, respectively, and are therefore straightforward indicators of differences in the functional composition of value added. We estimate Eq. (2) for each industry-specific sample

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[7] As we will discuss later, these emissions could relate to either the direct emissions only (i.e. the emissions taking place in country i’s transport equipment manufacturing industry itself) or the direct and indirect emissions (i.e. emissions in all industries in country i, that can be attributed to exports by the transport equipment industry).

by means of non-negative least squares regression. This type of approach imposes that value added creation (for whichever of the two functions) can never yield negative emissions. We expect the fabrication function to be more emission-intensive than the headquarters function, in particular in manufacturing industries. We do not restrict the regressions to reflect this but expect that the estimates for $\beta_1$will generally be larger than those for β_2.

In Section 5, we will use the coefficients obtained in this section as indicators of industry-specific 'world production and emission technologies', which take the functional composition of an industry in a country into account. We will then use these results in our accounting framework, aimed at quantifying the extent to which trade affects differences between national emission intensities and the global emission intensity. We start by discussing the data on which we rely.

3.1 Data

We take our data from two sources. First, the CO_2-emissions data are taken from the environmental satellite accounts of the World Input-Output Database (WIOD-2013 release; Timmer et al., 2015). Our analysis focuses on emissions by industries, and therefore disregards direct emissions by households. Data are available for 40 countries and a region labeled 'Rest of the World' (RoW). The data are available for 35 industries, which together span the entire economy of each country. An input-output table is needed to determine the amounts of CO_2 associated with exports not only emitted in the industries that export, but also further upstream. We take the 2008 world input-output table, also from WIOD. The table covers the same industries and countries as the emissions data.[8]

Second, we use the data on the functional composition of employment in industries as introduced by Timmer et al. (2019), which are compatible with the WIOD-2013 release and publicly available on the WIOD-website.[9] Based on data from population censuses, labor force surveys and additional sources of information, Timmer et al. constructed data in which labor income in each industry in each country is split into the remuneration of employees responsible for one of four business functions, labeled 'R&D', 'fabrication', 'marketing' and 'management'. The allocation of wage income to these functions is based on the occupations of workers (for instance, assemblers and machine operators are examples of occupations performing the fabrication function).[10] For the purpose of this paper, we distinguish between 'fabrication' and what we will for simplicity label 'headquarter (HQ) functions', which we define as the aggregate of 'R&D', 'marketing' and 'management' (following Bernard and Fort, 2015).[11] Our choice to aggregate these three functions into one is driven by our wish to keep the exposition as clear as possible and by the notion that exploratory analyses revealed

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[8] We could have used the 2009 input-output table, but decided against this in view of the short-run effects of the global financial crisis apparent in this table, which might have blurred more structural differences.

[9] See https://www.rug.nl/ggdc/valuechain/gvc-research/2018-joeg. Currently, data on the functional composition of employment in industries is not available yet for the WIOD-2016 release.

[10] In their analysis of the decline in routine work in advanced countries, Reijnders and de Vries (2018) used the same data, focusing on a more fine-grained classification of occupations.

[11] Buckley et al. (2020) use the label 'knowledge-intensive' functions for the same set of occupations).

that the main differences in the emission intensities are found between the fabrication and the HQ functions, rather than between ‘R&D’, ‘marketing’ and ‘management’.

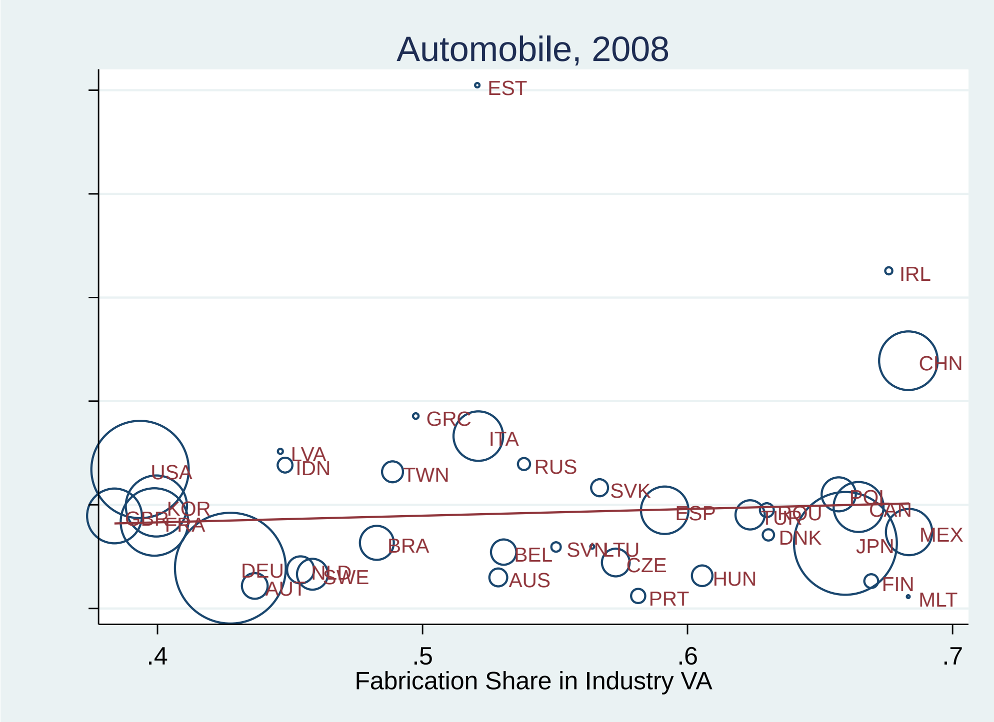
We need to split *value added* into parts generated by fabrication and HQ, respectively. As discussed above, we only have data on splits for *labor income*. We decided to allocate industry value added to both functions in proportion to their shares in labor income, given lack of sensible alternatives.[12]

We have excluded India, Luxembourg and Rest of the World from all regression samples. For India, this is in view of apparent large-scale occupational misclassifications of workers.[13] For Luxembourg, the emissions data appear suspect. The Rest of the World is an amalgam of very heterogeneous countries, for which mismeasurement issues are most probably much larger than for the countries included individually. After having removed data for these three countries, we estimated Eq. (2) for each of the 34 industries, based on 41 observations per industry.

3.2 Analysis of CO_2 intensities and industry-level functional compositions

In order to get a first idea of the differences in functional compositions of an industry across countries and the potential implications of these differences for the environmental performance, we give an illustration for what we (rather loosely) label the car manufacturing industry (formally, the transport equipment manufacturing industry).

Figure 3: CO_2 intensities and industry-level value added shares of fabrication (2008, Transport equipment manufacturing industry)



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[12] We follow Buckley et al. (2020) in this respect.

[13] These problems were confirmed to us in private communication with Gaaitzen de Vries, one of the co-authors of Timmer et al. (2019).

Note: The horizontal axis indicates the share of fabrication in industry value added. The vertical axis gives the emission intensity in the industry in kilotons of CO_2 per million dollars of value added. The surfaces of the circles are proportional to value added. Non-negative least squares regression, weighted by value added. *Source: Authors' computations based on the World Input-Output Database, 2013 release (Timmer et al., 2015) and functional income data from Timmer et al. (2019).*

The horizontal axis of Figure 3 depicts the differences in the share of industry value added attributed to the fabrication function, in 2008. The car industries in the countries considered appear to differ substantially in terms of their functional compositions. In countries like the US, Germany, France and the UK, the value added share of fabrication was about 0.4. At the other end of the spectrum, we find Mexico, China, Japan and Poland, with fabrication shares of close to 0.7.

Along the vertical axis, we plotted the CO_2 emissions intensity of the industry in the countries considered. Again, we observe a wide dispersion among the countries with sizable car industries. In Germany, this industry emitted about 0.5 kilotons of CO_2 per million dollar of value added, while its counterparts in Italy and China had emission intensities that were three to four times as high.

The regression line in Figure 3 (based on Eq. (2)) shows that there is a positive association between the share of fabrication income in value added and the CO_2 emitted in creating value added, as expected. The regression line has a slope of 0.067, implying that an increase in the share of fabrication value added of 0.1 on average implies an increase in the CO_2 emission intensity of 0.0067 kilotons of CO_2 per million dollars of value added.[14] One might argue that this is a small effect. It is important, though, to note that Figure 3 relates to emissions by this industry itself. It does not take emissions related to the use of intermediate inputs are not taken into account.

3.2 Including value chain effects in the analysis of CO_2 intensities and industry-level functional compositions

Functional specialization within an industry most probably does not only have implications for the emission intensity of the industry itself (the 'direct' effects), but also in upstream industries. Fabrication activities often require the use of machinery consuming a lot of electricity, while this might well be less important for HQ activities. If the power generation industry supplying this electricity mainly relies on fossil fuels, the indirect effects of the fabrication activities can be sizable. More generally speaking, the intermediate inputs required to produce might well depend on the functional composition of activity in an industry, having consequences for emissions anywhere in upstream industries. Hence, when analyzing the contributions of functional specialization on national emission intensities, emissions in all domestic industries that directly or indirectly contribute to the production of exported products should be taken into account.

Recent developments in input-output analysis allow us to compute the amount of CO_2 emitted in a country's territory due to a dollar exported by a given industry, e.g. the car

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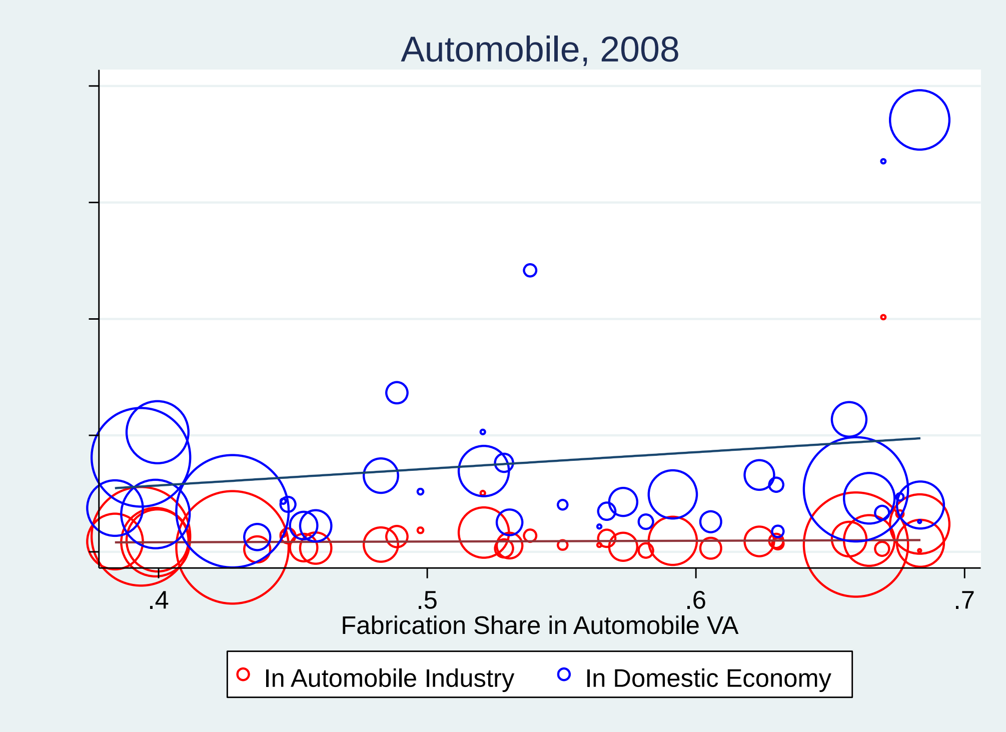
[14] The slope of the line in the figure is the difference between the estimated coefficients for β_1 and β_2 in Eq. (2).

manufacturing industry (e.g. Meng et al., 2018). Previously, very similar methods had been developed to compute the amount of domestic value added embodied in exports (e.g. Koopman et al., 2014, Los et al., 2016 and Los and Timmer, 2018). We obtained the results depicted in Figure 4 by using the hypothetical extraction-based approach advocated by Los and Timmer (2018). For each country, we first determined the value added by the domestic car manufacturing industry per dollar of its gross exports (the VAX-D concept, in the terminology of Los and Timmer). Next, we computed the CO_2 emissions by the domestic car industry due to a dollar of its gross exports. The ratios between these two are indicated by the vertical position of the red circles in the figure.[15]

Figure 4: Domestic CO_2 Embodied in Exported Value Added and Industry-Level Specialization in Fabrication (2008, Transport equipment manufacturing)



Note: The horizontal axis indicates the share of fabrication in industry value added. The vertical axis gives the emissions per dollar of car manufacturing value added in kilotons of CO_2 per million dollars of value added. Red circles: emissions in the car industry per dollar of domestic car manufacturing value added in the exports of the car manufacturing industry. Blue circles: emissions in all domestic industries per dollar of domestic car manufacturing value added in the exports of the car manufacturing industry. The surfaces of the circles are proportional to value added. Non-negative least squares regression, weighted by value added.

Source: Authors' computations based on the World Input-Output Database, 2013 release (Timmer et al., 2015) and functional income data from Timmer et al. (2019).

Next, we computed the CO_2 emissions by *all* domestic industries due to a dollar of gross exports by the car manufacturing industry. We then divided these by the value added by the domestic car industry per dollar of its gross exports to arrive at the quantifications of the *total*

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[15] The mathematical exposition of how the results underlying the observations depicted in Figure 4 have been obtained can be found in Appendix A.

effects, i.e. the domestic emissions per million dollars of car manufacturing exports. These intensities, which include the direct and the indirect effects are reflected by the vertical position of the blue circles.

The regression line through the red circles in Figure 4 is identical to the regression line in Figure 3. The emissions intensity is positively related to the share of fabrication in industry value added. New insights, however, are obtained by considering the blue circles and the associated regression line. For car manufacturing industries with a functional specialization in fabrication, industries in the same country tend to emit more CO_2 to produce the intermediate inputs it requires than for car manufacturing industries specialized in HQ functions, since the regression line has a slope 1.427, which is much steeper than the 0.067 of the regression line through the red circles. If the share of fabrication in car manufacturing value added increases by 0.1, the emissions in the domestic economy per million dollars of exports of this industry increase by 0.143 kilotons.

The Chinese car manufacturing industry might be considered as an outlier that affects the slope of the regression line considerably. We decided to continue including China for two main reasons. First, many of its industries are too large to be disregarded when considering deviations from the global average in our accounting analysis, which uses the regression results. Second, many countries that tend to have high national CO_2 emission intensities and have (according to anecdotal evidence) specialized in fabrication functions (like the Philippines, Thailand and Vietnam) could not be included because of lack of data but might well have featured in the upper right corner of Figure 4 if we would have had data.[16]

Figure 4 also shows that the indirect emissions tend to be considerably higher than the emissions by the car manufacturing industry itself, which reinforces our opinion that analyses of the effects of functional specialization in trade on the emissions performance of countries should take indirect effects into account. It might be somewhat risky, however, to make a strong case based on results for a single industry. In electronics (on a global scale), the indirect CO_2 emissions are more than 10 times as large as the direct effects, which is even higher than what we find for car manufacturing (6.7 times). We should note that we do not find that the indirect effects are larger than the direct effects for each and every industry. Still, e.g. in the chemicals industry, we find that the indirect effects are still close to 75% of the direct effects. We consider this as sufficient reason to take indirect emissions into account in analyzing the link between environmental performance and the functional composition of industries.

Table 1 shows the regression results for Eq. (2), for the complete set of industries, based on total domestic emissions due to a dollar of value added in the exports of the industry considered. For 14 out of the 34 industries, the non-negative least squares approach appears to be binding. The coefficients equal to 0.000 indicate that if ordinary least squares would have been used, increasing HQ-value added would reduce CO_2 emissions, which is implausible.

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[16] A logarithmic specification would fit the observations better but does not make much sense from a technological point of view. Such a specification would imply that there would be negative economies of scale in emissions.

Except for agriculture and a limited number of services industries, we find that fabrication functions are more emission-intensive than HQ functions, as expected. In many industries, the differences are substantial. For most manufacturing industries, the differences are larger than what we presented in Figure 4 for the car manufacturing industries. We also see that (with transportation services as prominent exceptions), exports by manufacturing industries tend to yield more emissions in the economy considered than exports by services industries. This implies that focusing exclusively on trade-induced functional specialization (without considering industry specialization) might lead to misleading conclusions regarding the impact of trade on national emission performance.

Table 1: Regression results by industry, Equation (2)

Sector Name	share Fab	share HQ	Sector Name	share Fab	share HQ
Agriculture	0.484	0.994	Construction	2.578	0.000
Mining	1.738	0.000	Maintainance	0.000	0.540
Food	1.737	0.003	Wholesale	0.233	0.315
Textile	2.469	0.000	Retail	0.551	0.332
Leather	1.985	0.000	Hotel	0.029	0.583
Wood	1.459	0.000	Land Transport	0.138	4.496
Paper	1.996	0.002	Water Transport	6.137	2.059
Oil	6.069	2.423	Air Transport	9.522	2.782
Chemical	5.839	0.000	Transport Supporting	1.541	0.000
Plastic	2.803	0.000	Telecom	0.609	0.194
Non-Metal	7.476	0.000	Finance	1.979	0.081
Metal	3.558	0.000	Real Estate	1.637	0.063
Machine	2.189	0.000	Biz Service	3.776	0.000
Electronics	3.994	0.000	Public	0.803	0.263
Automobile	1.427	0.000	Education	7.371	0.065
Other Manufacturing	1.840	0.000	Healthcare	1.463	0.364
Electricity	17.931	0.000	Other Service	3.170	0.099

Note: Dependent variable: kilotons of domestic CO_2 emissions per million dollar of value added by the exporting industry. Independent variables: fabrication function share in industry value added and headquarters functions share in industry value added. Non-negative least squares regression, weighted by value added. Full industry labels can be found in Appendix B.

Source: Authors' computations based on the World Input-Output Database, 2013 release (Timmer et al., 2015) and functional income data from Timmer et al. (2019).

The results presented in this section have shown that differences in the functional composition of industries have an impact on their emission intensity, in particular if indirect effects (on emissions in other domestic industries) are properly taken into account. As we have argued in Section 2, functional specialization has become a prominent aspect of international trade after GSCs became pervasive. In assessing the extent to which international trade affects national emissions performance, the results in this section show that this is most probably not an exercise that is only of academic interest, but that it also has empirical relevance. Hence, we will use the results regression results obtained in this section in the decomposition of differences in emissions performance across countries as introduced in the conclusion of Section 2.

4. Accounting for Trade-Induced Specialization in Assessing the Environmental Performance of Countries

In the previous section, we presented evidence that the environmental performance of industries is associated with the extent to which these are specialized in business function labeled fabrication. In what preceded those analyses, we discussed literature that argues that functional specialization is a prominent outcome of the processes allowing firms to spread their activities over countries without incurring excessive coordination costs. These two findings taken together suggest that functional specialization should be considered when accounting for differences in environmental performance of countries. In this section, we pursue this, using the decomposition framework announced in section 2.3:

Difference between a country's CO_2/GDP ratio and the global CO_2/GDP ratio =
Differences due to trade-induced industry specialization +
Differences due to trade-induced functional specialization +
Differences due to country-specific factors

The third term is always obtained as a residual. If only industry specialization is taken into account, the residual is not only due to country-specific factors, but confounded with effects that are actually caused by international trade.

In this section, we will first study the traditional approach, exclusively focusing on industry specialization. Next, we propose a framework to analyze the differences in industry specialization and functional specialization simultaneously, yielding a residual that exclusively contains country-specific factors.

4.1 Effects of trade-induced industry specialization on emission performance

Some industries produce products that are more emission-intensive than other products. If industry specialization as emphasized in classical and neoclassical trade theories takes place due to opportunities to exchange product internationally, this will thus have implications for the emission intensities of countries. We will study these using an approach that is inspired by Leontief (1953), the famous paper about the so-called Leontief Paradox, which relates to the relative abundance of production factors capital and labor and the intensity with which these are used in the production of traded products. As far as we are aware, this approach has been used twice in an environmental context. First, by Dietzenbacher and Mukhopadhyay (2007) in the study for India discussed in Section 2, and more recently by Xu et al. (2020) in a study for the United States.

Using an input-output table for the United States, Leontief (1953) first computed the amounts of labor and capital required to produce one million dollars of US exports, taking the industrial composition of this bundle into account. Next, he took the US imports bundle, and computed how much labor and capital would be needed if the United States would produce these imports (and the intermediate inputs to produce these in upstream stages of production) itself. We do something similar computing the CO_2 emissions associated with the export and input bundles of a country.[17] Given that we want to obtain country-specific differences from the global average as a residual, we cannot use country-specific technologies as contained in national input-output tables as Leontief (and Dietzenbacher and Mukhopadhyay, 2007, and Xu et al., 2020) did. Instead, we compute a global input-output table with 35 industries, by aggregating over countries, both row-wise and column-wise. This global input-output table provides information about the 'global technologies' (for each of the 35 industries). Using the associated Leontief inverse and global value added per unit of gross output, and post-multiplying these with the exports and imports bundles of country X, we computed the value added in each of the 35 industries in the exports and imports of Country X. The assumption is that these would have been produced using the average global technology. We do the same using global CO_2 to gross output ratios (one for each of the 35 industries) to compute the CO_2 in exports and imports.

The results are presented in Table 2. Column (1) gives the actual emission intensities of the fifteen largest countries in the world in 2008, which we presented in Figure 1 already. The actual global emission intensity is given in the last line. In column (2), we document the estimated emission intensities if all countries would use the same 'global technologies', in terms of both intermediate input requirements and emission coefficients. Differences across countries in this column are due to differences in the industrial composition of countries, due to differences in the composition of domestic final demand and trade. It is clear that the variation in intensities reported in this column is much smaller than in the first column, implying that differences in national technologies accounts for a large chunk of the actual variation. In columns (4) and (5), we report on the CO_2 intensities of the exports and imports, if both of them would be produced using world technologies. Differences between these are due to industry specialization.

Table 2: Accounting for differences in CO_2 emission intensities, effects of industry specialization (2008, 15 largest economies)

Country	(1) Actual CO2/VA	(2) CO2/VA GT	(3) CO2/VA GT trade-corrected	(4) CO2/VA GT in exports	(5) CO2/VA GT in imports	(6)=(4)/(5) Ratio of CO2/VA GT in exports and imports	(7) Actual difference to global	(8)=(2)-(3) Difference due to trade	(9)=(7)-(8) Residual difference to global
AUS	0.38	0.47	0.48	0.67	0.69	0.96	-0.06	0.00	-0.06
BRA	0.19	0.47	0.47	0.60	0.64	0.94	-0.24	0.00	-0.24
CAN	0.32	0.47	0.46	0.64	0.63	1.02	-0.11	0.01	-0.12
CHN	1.31	0.50	0.48	0.63	0.62	1.02	0.87	0.01	0.86
DEU	0.21	0.55	0.52	0.71	0.67	1.06	-0.23	0.03	-0.25
ESP	0.18	0.47	0.47	0.67	0.62	1.09	-0.26	0.00	-0.26
FRA	0.11	0.46	0.46	0.69	0.65	1.06	-0.33	0.01	-0.34
GBR	0.18	0.47	0.49	0.55	0.60	0.92	-0.26	-0.01	-0.24
IND	1.12	0.50	0.52	0.58	0.69	0.84	0.68	-0.02	0.70
ITA	0.18	0.50	0.50	0.67	0.66	1.01	-0.26	0.00	-0.26
JPN	0.21	0.45	0.44	0.68	0.66	1.03	-0.23	0.01	-0.23
KOR	0.61	0.53	0.51	0.70	0.67	1.05	0.17	0.01	0.16
MEX	0.33	0.50	0.52	0.58	0.67	0.87	-0.11	-0.02	-0.09
RUS	1.06	0.47	0.46	0.61	0.57	1.06	0.62	0.02	0.60
USA	0.32	0.40	0.41	0.55	0.62	0.88	-0.12	-0.02	-0.11

Note: GT stands for 'global technology'. Emission intensities in kilotons per million dollars of value added.

Source: Authors' computations based on the World Input-Output Database, 2013 release (Timmer et al., 2015).

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[17] See Appendix C for the mathematical details of the approach we adopt.

Using the global technologies, CO_2 emissions directly and indirectly involved in producing a million dollar of exports vary considerably across industries, from 2.18 kilotons for non-metallic mineral products (which includes the production of cement), to 1.02 kilotons for basic and fabricated metals 1.02, 0.48 and 0.47 kilotons for transport equipment and electronics, respectively. The extremely low emissions associated with exports of financial intermediation services (0.13 kilotons per million dollars of exports) are clearly reflected in the low emission intensity of UK exports.

Column (6), which presents what Antweiler (1996) coined the “Pollution Terms of Trade Index”, shows that Germany and Spain are among the countries that had the most unfavorable industry specialization, in the sense that their exports would have been clearly more CO2-intensive than their imports if differences in technologies are disregarded. For India and Mexico, the opposite holds: their imports would have been much dirtier than their exports.

The effects of the differences in the composition of exports and imports bundles on the national emission intensities are obtained by observing the differences between column (2) and column (3), presented in column (8). The degree to which the results in column (6) lead to differences between (2) and (3) depends on the openness of countries (the size of trade relative to that of the domestic economy) and the trade balance (the magnitude of exports relative to that of imports). The differences tend to be rather small if compared to the actual differences to the global average (compare columns (7) and (8)). The result for Germany is the largest among the small differences. Germany’s trade pattern in 2008 was such that its industry specialization due to trade affected its emission performance negatively, even though the country produced considerably less emission-intensive than the world. The residual differences reported in column (9) are large.

These results are in line with results as obtained in, for example, Dietzenbacher and Mukhopadhyay (2007) and Xu et al. (2020), which used similar approaches. Trade-induced industry specialization alone does not have much of an impact on the environmental performance of countries, which corresponds to what many of the macro-oriented contributions to the literature on the pollution haven hypothesis as reviewed in Section 2 found.

4.2 Effects of trade-induced specialization on emission performance, including functional specialization

In order to quantify the effects of functional specialization next to those of trade-induced industry specialization, we do not only consider the industries that export and from which imports are used, but also the functional composition of these. According to Figure 2 above, imports from the U.S. car manufacturing industry involve a very different functional bundle (with a low share of fabrication value added) than imports from the Mexican car manufacturing industry (with a high share of fabrication value added). We have also provided evidence that fabrication functions tend to be much more emission-intensive than HQ functions (see Table 1 above).

We first compute the domestic value added of each industry in the exports of that industry and split this into fabrication value added and HQ value added. Next, we multiply these two value added components with the regression coefficients reported in Table 1, which represent the global technologies: how much emissions are associated with the exports of one million dollar of fabrication value added of an industry and of one million dollar of HQ value added of that industry, based on the global sample of countries?[18] As discussed before, the coefficients in Table 1 take indirect effects into account already, so we do not have to perform any additional input-output manipulations anymore.

We performed similar computations for imports of products from each industry, on a partner country by partner country basis: the fabrication value added in imports from industry A in country X is added to the fabrication value added in imports from the same industry A in countries Y and Z to arrive at all fabrication value added by industries A, which is then multiplied by the corresponding regression coefficient. Next, we do the same for HQ value added in imports from industry A in the various partner countries, before continuing with imports from industry B.

We present the results in Table 3.

Table 3: Accounting for differences in CO2 emission intensities, effects of industry specialization and functional specialization combined (2008, 15 largest economies)

Country	(1) Actual CO2/VA	(2) CO2/VA GT trade-corrected	(3) CO2 per $1 OwnVA GT in exports	(4) CO2 per $1 OwnVA GT in imports	(5)=(3)/(4) Ratio of CO2/$1 OwnVA GT in exports and imports	(6) Actual difference to global	(7)=(1)-(2) Difference due to trade	(8)=(6)-(7) Residual difference to global
AUS	0.38	0.37	1.08	1.02	1.06	-0.06	0.01	-0.07
BRA	0.19	0.21	1.08	1.30	0.83	-0.24	-0.01	-0.23
CAN	0.32	0.25	1.28	0.86	1.48	-0.11	0.07	-0.18
CHN	1.31	1.23	2.04	1.29	1.58	0.87	0.08	0.79
DEU	0.21	0.18	1.17	0.99	1.18	-0.23	0.03	-0.26
ESP	0.18	0.22	1.20	1.72	0.70	-0.26	-0.05	-0.21
FRA	0.11	0.14	1.15	1.57	0.73	-0.33	-0.04	-0.30
GBR	0.18	0.22	0.66	0.90	0.73	-0.26	-0.03	-0.22
IND	1.12	1.19	0.66	1.59	0.42	0.68	-0.08	0.76
ITA	0.18	0.22	1.17	1.50	0.78	-0.26	-0.03	-0.22
JPN	0.21	0.19	1.65	1.30	1.27	-0.23	0.03	-0.25
KOR	0.61	0.72	1.35	1.94	0.69	0.17	-0.11	0.28
MEX	0.33	0.31	1.32	1.14	1.16	-0.11	0.02	-0.13
RUS	1.06	0.93	1.33	0.54	2.48	0.62	0.13	0.49
USA	0.32	0.36	0.75	1.58	0.48	-0.12	-0.05	-0.08
Global	0.44							

Note: GT stands for ‘global technology’. Emission intensities in kilotons per million dollars of value added.

Source: Authors’ computations based on the World Input-Output Database, 2013 release (Timmer et al., 2015) and functional income data from Timmer et al. (2019).

The organization of the table resembles that of Table 2. In Table 3, column (5) again presents Antweiler’s “Pollution Terms of Trade Index”. It shows that the differences between the emission intensities of exports and imports tend to be much more pronounced than if only industry specialization is taken into account. The results for China are a case in point. Whereas a dollar of its exports were only 2% more polluting than its imports (disregarding technological differences across countries in the world), we find that if functional specialization is also considered, this difference increases to 58%. For Russia, we find a

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[18] This approach views the vertical distances between the observations and the regression lines in Figures 3 and 4 as differences from the global average due to country-specific factors.

similar and even more prominent effect. For the United States, we find the opposite: if functional specialization is taken into account, the ratio between the emission intensities of its exports and imports falls from 0.88 (if only industry specialization is considered) to 0.48. We already saw that the transportation manufacturing industry in the United States is rather strongly specialized in HQ functions, and this industry is not an exception in the U.S. economy.[19]

If we consider columns (6)-(8), we observe that the contributions of trade to differences in emission intensities are no longer negligible. For China, about 9% of the gap between its national emission intensity and the global average (0.08 of 0.87 kilotons per million dollars of GDP) can be attributed to its trade specialization. For Russia, the effects of trade even amount to more than 20% of the actual difference. For some advanced countries, we find that trade had positive effects on its emission performance. For the United States, for example, almost half of the gap between its low emission intensity and the global average turns out to be due to its trade specialization. Similar, but less substantial results are found for a number of countries in Western Europe, such as France, Italy and the United Kingdom. This might be viewed as evidence supporting the pollution haven hypothesis, but we definitely do not find a ‘universal law’ indicating that advanced countries have favorable trade patterns and that poorer countries trade in ways that harm their national emission intensities. Germany and Mexico are examples of these two kinds of exceptions, respectively.

5. Conclusions and Implications

In this paper, we add a new perspective to the question to which extent international trade contributes to differences in national environmental performance, measured by us as the domestic CO_2 emissions per dollar of value added. As the literature review in Section 2 showed, most macro-economic studies (in which industries are the smallest unit of analysis) fail to find substantial effects, while there is micro-level evidence that firms tend to take differences in the costs of pollution into account when picking a location or consider relocation of the pollution-intensive activities in their production processes. Recently, Cherniwchan et al. (2017) argued that an explicit focus on within-industry heterogeneity could be helpful in bridging the gap between the two types of findings. Rather than focusing on within-industry heterogeneity in productivity levels as advocated by Cherniwchan et al., we focus on heterogeneity in the type of business functions performed by industries in countries, even if they share the same label in industry classifications. Based on data on the occupational composition of labor income using data from Timmer et al. (2019), we make a distinction between the fabrication function and the headquarter function and show that the shares of these two functions in industry value added can vary considerably across countries.

Using data from the World Input-Output Database for 2008, we show that exports of industries that are specialized in fabrication tend to cause more emissions than industries with

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[19] We are considerably less confident about the results for India (see footnote 13), but have included them to cover the full set of the fifteen largest economy of the world.

the same label that are specialized in HQ functions. We then show that considerably larger parts of differences in national emission intensities across the fifteen largest economies in the world can be attributed to differences in international trade patterns. We estimate, for example, that thirteen per cent of the difference between the Chinese CO_2 emission intensity and the global average, whereas this share is only slightly above one per cent if only industry specialization is considered.

Our findings might have implications for research into relationships between trade and the environment (such as analysis into the pollution haven hypothesis, PHH) and between trade, growth and the environment (such as studying the existence of the environmental Kuznets curve, EKC). Although our results do not suggest a ‘universal law’, but generally advanced countries with low emission intensities seem to benefit significantly from a functional specialization into HQ functions. This might hint at more empirical support for PHH and at less support for the EKC. Still, much more work is needed to arrive at more definitive conclusions. The set of countries for which we can do our analysis does not contain many poorer emerging countries. If indicators for functional specialization within industries would become available with an industry classification compatible with the recently updated OECD-ICIO database, many more emerging countries could be incorporated. Another data improvement that might improve the accuracy of the results of analyses like ours considerably relates to the assumed homogeneity of firms within an industry *in a given country* (rather than *across countries*, as studied in this paper). It is well-known that exporting firms operate technologies that differ from the technologies used by firms that only serve domestic markets (see, Duan et al., 2022, for the case of Chinese regions). It is not unlikely that such heterogeneities across firms extend to their functional compositions. So-called extended input-output tables could be helpful in addressing such issues, but these are not yet available on a global scale.

The analysis in this paper might shed new light on important policy issues. A sizable body of literature has emerged focusing on the question to what extent countries are responsible for emissions (see e.g. Lenzen et al., 2007; Kander et al., 2015; and Dietzenbacher et al., 2020). The answers to such questions are important in negotiations about sharing the short-run costs of reducing global emissions. The decompositions in this paper provide important quantifications of the extent to which countries emission intensities of countries differ from global averages due to country-specific factors, or due to trade, taking an aspect of trade that has become important with the proliferation of global supply chains explicitly into account (in contrast to the papers mentioned).

Finally, functional specialization might be an aspect that should receive attention in discussions about ambitious initiatives like the European Green Deal and associated trade policies. Discussions about the Carbon Border Adjustment Mechanism (tariffs on ‘dirty’ products imported by EU member states) and its compliance with WTO trade regulations might become increasingly relevant if pollution haven effects are stronger than thought before (see also de Melo and Solleder, 2020, about related implications of trade barriers regarding environmental goods). From a policy perspective, it might also be interesting to find out whether environmental provisions in preferential trade agreements (Brandi et al., 2020) have an impact on patterns of within-industry functional specialization.

References

Antweiler, W. (1996), “The Pollution Terms of Trade”, *Economic Systems Research*, 8, 361–365.

Antweiler, W., B.R. Copeland and M.S. Taylor (2001), “Is Free Trade Good for the Environment?”, *American Economic Review*, 91, 877-908.

Arto, I. and E. Dietzenbacher (2014), "Drivers of the Growth in Global Greenhouse Gas Emissions", *Environmental Science & Technology*, 48, 5388-5394.

Baldwin, R.E. (2016), *The Great Convergence; Information Technology and the New Globalization*, Cambridge MA: Harvard University Press.

Barrows, G. and H. Ollivier (2021), “Foreign Demand, Developing Country Exports, and CO_2 Emissions”, *Journal of Development Economics*, 149, 102587.

Becker, R.A. and J.V. Henderson (2000), “Effects of Air Quality Regulations on Polluting Industries”, *Journal of Political Economy*, 108, 379-421.

Bernard, A.B. and T.C. Fort (2015), “Factoryless Goods Producing Firms”, *American Economic Review*, 105, 518-523.

Bombardini, M., and B. Li (2020), “Trade, Pollution and Mortality in China”, *Journal of International Economics*, 125, 103321.

Brandi, C., J. Schwab, A. Berger and J.-F. Morin (2020), “Do Environmental Provisions in Trade Agreements Make Exports from Developing Countries Greener?”, *World Development*, 129, 104899.

Buckley, P.J., R. Strange, M.P. Timmer and G.J. de Vries (2020), “Catching-Up in the Global Factory: Analysis and Policy Implications”, *Journal of International Business Policy*, 3, 79-106.

Cherniwchan, J., B.R, Copeland and M.S. Taylor (2017), “Trade and the Environment: New Methods, Measurements, and Results”, *Annual Review of Economics*, 9, 59-85.

Cole, M.A. (2004), “Trade, the Pollution Haven Hypothesis and the Environmental Kuznets Curve: Examining the Linkages”, *Ecological Economics*, 48, 71-81.

Cole, M.A., R.J.R. Elliott and T. Okubo (2010), “Trade, Environmental Regulations and Industrial Mobility”, *Ecological Economics*, 69, 1995-2002.

Copeland, B.R. and M.S. Taylor (2003), *Trade and the Environment: Theory and Evidence*, Princeton: Princeton University Press.

Davis, S.J. and K. Caldeira (2010), "Consumption-Based Accounting of CO2 Emissions", *Proceedings of the National Academy of Sciences*, 107, 5687-5692.

Dietzenbacher, E., B. Los, R. Stehrer, M.P. Timmer and G.J. de Vries (2013), “The Construction of World Input-Output Tables in the WIOD Project”, *Economic Systems Research*, 25, 71-98.

Dietzenbacher, E., I. Cazcarro and I. Arto (2020), “Towards a More Effective Climate Policy on International Trade”, *Nature Communications*, 11, 1130.

Dietzenbacher, E. and K. Mukhopadhyay (2007), “An Empirical Examination of the Pollution Haven Hypothesis for India: Towards a Green Leontief Paradox?”, *Environmental and Resource Economics*, 36, 427-449.

Duan, Y., E. Dietzenbacher, B. Los and C. Yang (2022), “Processing Trade in Chinese Interregional Input-Output Tables: Construction and Application”, *Economic Systems Research*, forthcoming.

Ederington, J., A. Levinson and J. Minier (2005), “Footloose and Pollution-Free”, *Review of Economics and Statistics*, 87, 92-99.

Eskeland, G.S. and A.E. Harrison (2003), "Moving to Greener Pastures? Multinationals and the Pollution Haven Hypothesis", *Journal of Development Economics*, 70, 1-23.

Gereffi, G. and K. Fernandez-Stark (2016), *Global Value Chain Analysis: A Primer*, 2nd edition. Duke University, mimeo.

Grossman, G.M. and A. Krueger (1993), “Environmental Impacts of a North American Free Trade Agreement”, in: P.M. Garber (ed.) *The Mexico-U.S. Free Trade Agreement*, Cambridge MA: MIT Press, 13-56.

Grossman, G.M. and E. Rossi-Hansberg (2008), "Trading Tasks: A Simple Theory of Offshoring", *American Economic Review*, 98, 1978-1997.

Hering, L. and S. Poncet (2014), “Environmental Policy and Exports: Evidence from Chinese Cities”, *Journal of Environmental Economics and Management*, 68, 296-318.

Kander, A., M. Jiborn, D.D. Moran and T.O. Wiedmann (2015), “National Greenhouse-Gas Accounting for Effective Climate Policy on International Trade”, *Nature Climate Change*, 5, 431-435.

Koopman, R.B., Z. Wang and S.-J. Wei (2014), "Tracing Value-Added and Double Counting in Gross Exports", *American Economic Review*, 104, 459-494.

Lenzen, M., J. Murray, F. Sack and T. Wiedmann (2007), “Shared Producer and Consumer Responsibility – Theory and Practice”, *Ecological Economics*, 61, 27-42.

Leontief, W. (1953), “Domestic Production and Foreign Trade: The American Capital Position Re-Examined”, *Proceedings of the American Philosophical Society*, 97, 332-349.

Levinson, A. and M.S. Taylor (2008), “Unmasking the Pollution Haven Effect”, *International Economic Review*, 49, 223-254.

López, L.A., G. Arce and J.E. Zafrilla (2013), “Parcelling Virtual Carbon in the Pollution Haven Hypothesis”, *Energy Economics*, 39, 177-186.

Los, B. and M.P. Timmer (2018), "Measuring Bilateral Exports of Value Added: A Unified Framework", in: N. Ahmad, B. Moulton, J.D. Richardson and P. van de Ven (eds.), *The Challenges of Globalization in the Measurement of National Accounts* (Chicago: Chicago University Press), forthcoming.

Los, B., M.P. Timmer and G.J. de Vries (2016), "Tracing Value-Added and Double Counting in Gross Exports: Comment", *American Economic Review*, 106, 1958- 1966.

de Melo, J. and J.-M. Solleder (2020), “Barriers to Trade in Environmental Goods: How Important they are and What Should Developing Countries Expect from their Removal”, *World Development*, 130, 104910.

Meng, B., G.P. Peters, Z. Wang and M. Li (2018), "Tracing CO_2 Emissions in Global Value Chains", *Energy Economics*, 73, 24-42.

Mudambi, R. (2008), “Location, Control and Innovation in Knowledge-Intensive Industries”, *Journal of Economic Geography*, 8, 699-725.

Peters, G.P. and E.G. Hertwich (2008), "Post-Kyoto Greenhouse Gas Inventories: Production versus Consumption", *Climatic Change*, 86, 51-66.

Peters, G.P., J.C. Minx, C.L. Weber and O. Edenhofer (2011), “Growth in Emission Transfers via International Trade 1990-2008”, *Proceedings of the National Academy of Sciences*, 108, 8903-8908.

Rahman, M.D.A., B. Los, A. Owen and M. Lenzen (2022), “Multi-Level Comparisons of Input-Output Tables using Cross-Entropy Indicators”, *Economic Systems Research*, forthcoming.

Reijnders, L.S. and G.J. de Vries (2018), “Technology, Offshoring and the Rise of Non-Routine Jobs”, *Journal of Development Economics*, 135, 412-432.

Serrano, M. and E. Dietzenbacher (2010), “Responsibility and Trade Emission Balances: An Evaluation of Approaches”, *Ecological Economics*, 69, 2224-2232.

Shapiro, J.S. and R. Walker (2018), “Why is Pollution from US Manufacturing Declining? The Roles of Environmental Regulation, Productivity, and Trade”, *American Economic Review*, 108, 3814-3854.

Stern, D.I. (2004), “The Rise and Fall of the Environmental Kuznets Curve”, *World Development*, 32, 1419-1439.

Timmer, M.P., E. Dietzenbacher, B. Los, R. Stehrer and G.J. de Vries (2015), "An Illustrated User Guide to the World Input-Output Database: The Case of Global Automotive Production", *Review of International Economics*, 23, 575-605.

Timmer, M.P., S. Miroudot and G.J. de Vries (2019), "Functional Specialisation in Trade", *Journal of Economic Geography*, 19, 1-30.

Tukker, A. and E. Dietzenbacher (2013), “Global Multiregional Input-Output Frameworks: An Introduction and Outlook”, *Economic Systems Research*, 25, 1-19.

Wiedmann, T., H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West and K. Kanemoto (2015), "The Material Footprint of Nations", *Proceedings of the National Academy of Sciences*, 112, 6271-6276.

Wilting, H.C. and K. Vringer (2009), “Carbon and Land Use Accounting from a Producer’s and a Consumer’s Perspective – An Empirical Examination Covering the World”, *Economic Systems Research*, 21, 291-310.

Xu, Y., E. Dietzenbacher and B. Los (2020), “International Trade and Air Pollution in the United States”, *Ecological Economics*, 171, 1-10.

Appendix A: The measurement of domestic CO_2 emissions in exports

We adapt the VAX-D approach proposed by Los and Timmer (2018) to compute value added and CO_2 emissions in the exports of an industry in a country (see Figure 4), based on global input-output tables. Let us denote the number of countries (including the Rest of the World, to ensure that the global economy is covered entirely) by c and the number of industries by n. The matrix of intermediate input requirements per unit of gross output can then be represented by the ncxnc matrix **A**:[20]

$$A = \begin{bmatrix} a_{rr}^{ii} & a_{rr}^{ij} & a_{rs}^{ij} \\ a_{rr}^{ji} & A_{rr}^{jj} & A_{rs}^{jk} \\ a_{sr}^{ki} & A_{sr}^{kj} & A_{ss}^{kk} \end{bmatrix} \tag{A.1}$$

In this expression, r denotes the country of interest (the 'focal country'), while s stands for all other countries in the global input-output table. i denotes the industry of interest, and j indicates all other industries in r.[21] The first symbol in the indices refers to the supplying industries and countries, the second denotes the using industries and countries. The scalar a_{rr}^{ii} thus represents the inputs required by industry i in country r, as delivered by that industry itself. The industries in countries s are indicated by k. The other parts of **A** as expressed in Eq. (A.1) have multiple rows and/or columns, because j, k and s represent multiple industries and countries, respectively. The element A_{ss}^{kk} is an $n(c$-$1)$x$n(c$-$1)$ matrix with the intermediate input requirements per dollar of output of each of the industries in each of the non-focal countries, for products sold by each of the industries in the non-focal countries.

In a similar vein, we can represent the ncxc matrix with sales to final users as[22]

$$Y = \begin{bmatrix} y_{rr}^{i} & y_{rs}^{i} \\ y_{rr}^{j} & Y_{rs}^{j} \\ y_{sr}^{k} & Y_{ss}^{k} \end{bmatrix} \tag{A.2}$$

in which the upper indices denote the supplying industries. Finally, we express the ncx1 vectors with value added and CO_2 emission coefficients (defined as the ratios of value added and emissions, respectively, to gross output) as

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[20] In this appendix, we follow the convention adopted by input-output researchers to represent matrices by bold capital symbols, vectors by bold lowercase symbols and scalars by italicized lowercase symbols. Primes stand for transposition and hats for diagonal matrices.

[21] Note that the order of rows an columns of an input-output table can always be permuted in such a way that the industries and countries appear in an order that is in line with the structure of the matrices and vectors presented here.

[22] We aggregate over various types of final use, such as household consumption and gross fixed capital formation, since the use of final products is not relevant in the context of this paper.

$$v = \begin{bmatrix} v_r^i \\ v_r^j \\ v_s^k \end{bmatrix} \text{ and } e = \begin{bmatrix} e_r^i \\ e_r^j \\ e_s^k \end{bmatrix} \qquad \text{(A.3)}$$

Following well-known input-output logic, the actual value added (**w**) in each of the industries and countries can now be represented by Eq. (A.4), and the actual emissions (**d**) in each of the industries and countries as Eq. (A.5):

$$w = v'(I-A)^{-1}Yi \qquad \text{(A.4)}$$

$$d = e'(I-A)^{-1}Yi \qquad \text{(A.5)}$$

In these equations, **i** stands for an *c*x1 summation vector and **I** for an *nc*x*nc* identity matrix. The matrix $(I-A)^{-1}$ is the well-known Leontief inverse.

The approach introduced by Los et al. (2016) and Los and Timmer (2018) proceeds by defining hypothetical matrices $\mathbf{A}^*$ and $\mathbf{Y}^*$, in which the export flows of interest are set equal to zero. In the context of this paper, this means that we define

$$A^{¿} = \begin{bmatrix} a_{rr}^{ii} & a_{rr}^{ij} & 0 \\ a_{rr}^{ji} & A_{rr}^{jj} & A_{rs}^{jk} \\ a_{sr}^{ki} & A_{sr}^{kj} & A_{ss}^{kk} \end{bmatrix} \text{ and } Y^{¿} = \begin{bmatrix} y_{rr}^{i} & 0 \\ y_{rr}^{j} & Y_{rs}^{j} \\ y_{sr}^{k} & Y_{ss}^{k} \end{bmatrix} \qquad \text{(A.6)}$$

The expressions in Eq. (A.6) indicate that we assume that the exports of industry *i* in country *r* to any of the industries *k* in any of the countries *s* are zero, and that industry *i* in *r* does not sell to final users in any of the countries *s* either. We can now compute the hypothetical value added and emission levels as

$$w^{¿} = v'(I-A^{¿})^{-1}Y^{¿}i \qquad \text{(A.7)}$$

$$d^{¿} = e'(I-A^{¿})^{-1}Y^{¿}i \qquad \text{(A.8)}$$

The first element of the vector $\mathbf{w}\text{-}\mathbf{w}^*$ now gives the value added by industry *i* in *r* in its own exports, while the first element of the vector $\mathbf{d}\text{-}\mathbf{d}^*$ represents the CO2 emission by industry *i* in *r* attributable to its own exports. The vertical position of the red circles in Figure 4 is now given by the ratio between the two differences: $(d\text{-}d^*)_1/(w\text{-}w^*)_1$.

To determine the vertical position of the blue circles in Figure 4, we do not only consider the emissions in industry *i* in country *r*, but emissions by all industries in that country (taking indirect effects into account). Hence, we compute $\sum_{m=1}^{n}(d_m - d_m^{¿})/(w_1 ¿ - w_1^{¿}) ¿$ to arrive at these numbers.

Appendix B: Industry classification

1.	Agriculture, Forestry, Hunting and Fishing	18.	Construction
2.	Mining and Quarrying	19.	Sale and Maintenance of Motor Vehicles
3.	Food, Beverages and Tobacco	20.	Wholesale Trade, exc. for Motor Vehicles
4.	Textiles and Textile Products	21.	Retail Trade, exc. for Motor Vehicles
5.	Leather, Leather Products and Footwear	22.	Hotels and Restaurants
6.	Wood and Products of Wood and Cork	23.	Inland Transport
7.	Pup, Paper, Printing and Publishing	24.	Water Transport
8.	Coke, Refined Fuel and Nuclear Fuel	25.	Air Transport
9.	Chemicals and Chemical Products	26.	Other Supporting Transport Services; Travel Agencies
10.	Rubber and Plastics	27.	Post and Telecommunications
11.	Other Non-Metallic Mineral Products	28.	Financial Intermediation
12.	Basic metals and Fabricated Metal Products	29.	Real Estate Activities
13.	Machinery, nec.	30.	Renting of Machinery and Equipment; Other Business Services
14.	Electrical and Optical Equipment	31.	Public Administration and Defence
15.	Transport Equipment Manufacturing	32.	Education
16.	Other Manufacturing; Recycling	33.	Health and Social Work
17.	Electricity; Gas and Water Supply	34.	Other Social and Personal Services

Note: The industry “Private Households with Employed Persons” has not been included in the analyses, because it has zero output for many countries in WIOD. This does not affect the results, since the industry does not export and has very low CO_2 emissions, if any.

Appendix C: Quantifying global technologies from world input-output tables and computing the emissions in exports and imports using these global technologies

1. *Quantifying global technologies from world input-output tables*

For the analysis of the impacts of trade-induced industry specialization on the environmental performance of countries (in subsection 4.1), quantitative characterizations of global technologies are needed. Such characterizations of technologies for industries in specific countries can be obtained in a straightforward manner from world input-output tables, but to obtain these at the global level, some matrix algebraic operations are needed. We present these formally in this appendix.

What is needed is a matrix with global intermediate input coefficients ($\mathbf{A}^g$), a vector with global emission coefficients ($\mathbf{e}^g$) and a vector with global value added coefficients ($\mathbf{v}^g$). Like in Appendix A, we denote the number of countries by *c* and the number of industries per country by *n*. $\mathbf{A}^g$ is an *n*x*n* matrix, and $\mathbf{e}^g$ and $\mathbf{v}^g$ are *n*x1 vectors. To compute these, the *nc*x*nc* matrix with intermediate input deliveries **Z** is needed, as well as the *nc*x1 vector of gross output levels **x**, the *nc*x1 vector with value added levels **w** and the *nc*x1 vector with emission levels **d**. **Z**, **x**, **w** and **d** all contain information for each of the industries in each country and can be taken directly from world input-output tables and associated environmental satellite accounts. The matrix and vectors can be expressed in partitioned form as

$$Z \equiv \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1c} \\ Z_{21} & Z_{22} & \cdots & Z_{2c} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{c1} & Z_{c2} & \cdots & Z_{cc} \end{bmatrix},\ x \equiv \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_c \end{bmatrix},\ w \equiv \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_c \end{bmatrix},\ \text{and } d \equiv \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_c \end{bmatrix} \qquad \text{(A.9)}$$

The block matrices in **Z** have dimensions *n*x*n*, while the vectors in **x**, **w** and **d** are *n*x1 (column) vectors. We obtain the *n*x*n* matrix $\mathbf{Z}^g$ with deliveries of each of the ‘global’ industries to each of the global industries by aggregating over each of the blocks in **Z**: the deliveries of e.g. the German steel industry to the German car manufacturing industry are added to the deliveries of the British steel industry to the German car manufacturing industry, and to those of the British steel industry to the French car manufacturing industry, etc.:

$$Z^g = \begin{bmatrix} I & I & \cdots & I \end{bmatrix} \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1c} \\ Z_{21} & Z_{22} & \cdots & Z_{2c} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{c1} & Z_{c2} & \cdots & Z_{cc} \end{bmatrix} \begin{bmatrix} I \\ I \\ \vdots \\ I \end{bmatrix} \qquad \text{(A.10)}$$

in which **I** indicates an identity matrix with *n* rows and *n* columns. In a similar vein, we compute

$$x^g = ¿ \begin{bmatrix} I & I & \cdots & I \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_c \end{bmatrix}, w^g = ¿ \begin{bmatrix} I & I & \cdots & I \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_c \end{bmatrix} \text{ and } d^g = ¿ \begin{bmatrix} I & I & \cdots & I \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_c \end{bmatrix} \quad \text{(A.11)}$$

These are all *n*x1 vectors, representing the output values, value added and emission levels, respectively, for each of the *n* global industries. With the information contained in the matrix and vectors in Eqs. (A.10) and (A.11), quantitative characterizations of global technologies can be obtained in the usual way:

$$A^g = Z^g \left(\hat{x}^g\right)^{-1}, \; v^g = \left(\hat{x}^g\right)^{-1} w^g \text{ and } e^g = \left(\hat{x}^g\right)^{-1} d^g \quad \text{(A.12)}$$

2. *Determining the emissions involved in trade, according to the global technologies*

The *ncxc* final demand block **Y** of an world input-output table has the structure

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1c} \\ y_{21} & y_{22} & \cdots & y_{2c} \\ \vdots & \vdots & \ddots & \vdots \\ y_{c1} & y_{c2} & \cdots & y_{cc} \end{bmatrix}$$

in which the blocks are column vectors with *n* elements. For country 1, its (*n*x1) export vector can now be computed as

$$\exp = \begin{bmatrix} Z_{12} & \cdots & Z_{1c} \end{bmatrix} i + \begin{bmatrix} y_{12} & \cdots & y_{1c} \end{bmatrix} i \quad \text{(A.13)}$$

in which **i** stands for summation vectors (containing ones) of appropriate length, like in Appendix A. The exports vector contains both exports of intermediate products and products for final use. For country 1, the (*n*x1) imports vector is given by

$$imp = \begin{bmatrix} Z_{21} & \cdots & Z_{c1} \end{bmatrix} i + \begin{bmatrix} y_{21} & \cdots & y_{c1} \end{bmatrix} i \quad \text{(A.14)}$$

The blocks in Eq. (A.14) are ordered in a way that differs from how they appear in the matrices **Z** and **Y**, to ensure that aggregation yields an imports vector by supplying industry, aggregated over countries that supply.

The CO_2 emissions by country 1 that can be attributed to its exports if the global technologies would have been used can now be expressed as $d^{\exp} = (e ¿¿ g)'(I - A^g)\exp ¿$ and the value added these would have generated as $w^{\exp} = (v ¿¿ g)'(I - A^g)\exp ¿$. Similarly, the emissions associated with its imports and the value added associated with these can be expressed as $d^{imp} = (e ¿¿ g)'(I - A^g) imp ¿$ and $w^{imp} = (v ¿¿ g)'(I - A^g) imp ¿$, respectively. The results as reported in subsection 4.1 have been computed using these expressions.