Sharing Responsibility for Trade-Related Emissions Based on Economic Benefits

Michael Jakob[a,*], Hauke Ward[b,a,c,#], Jan Christoph Steckel [a,c]

(a) Mercator Research Institute on Global Commons and Climate Change, 10829 Berlin, Germany
(b) Institute of Environmental Sciences (CML), Department of Industrial Ecology, Leiden University, P.O.Box 9518, 2300, RA, Leiden, the Netherlands
(c) Potsdam Institute for Climate Impact Research, Postfach 60 12 03, 14412 Potsdam, Germany

(*) Corresponding author:
Name: Michael Jakob
Postal address: Torgauer Str. 12-15, 10829 Berlin
Email address: jakob@mcc-berlin.net
Telephone number: +49 30 33 85 537 202

(#) Corresponding author:
Name: Hauke Ward
Postal address: Department of Industrial Ecology, Leiden University, P.O.Box 9518, 2300, RA, Leiden
Email address: h.ward@cml.leidenuniv.nl
Telephone number: +31 71 527 6808

Abstract

How to share responsibility for greenhouse gas emissions between consumers and producers is a highly sensitive question in international climate policy negotiations. Traditional allocations to the producer of emissions have frequently be complemented by 'Consumption-Based Accounting' (CBA) schemes that suggest greenhouse gas emissions generated to produce traded goods and services should be attributed to their final consumers. Both approaches lack a sound foundation in economic theory, i.e. they do not consider the economic benefits accruing to producers or consumers if carbon emissions do not carry a price that reflect their social costs. We build on well-established economic theory to derive how to share responsibility for trade-related emissions between producers and consumers and apply this novel approach for the most prominent bilateral trade relationships using multi-regional input-output data. We propose to use an 'Economic Benefit Shared Responsibility' (EBSR) scheme, where China is attributed significantly higher responsibility for emissions than in CBA, while lower emissions and responsibility are attributed to both the US and the EU.

Keywords: Climate Change Mitigation, Trade-related Emissions, Emission Accounting, Economic benefit analysis, Economic counterfactual analysis, Responsibility

1. Introduction

In an integrated world economy, production is increasingly distributed around the globe (Timmer et al. 2014; Baldwin 2009; Hummels 2007). The fragmentation of supply chains and the geographical separation of consumers and producers represent a serious challenge for climate policy, as it complicates the assignation of responsibility for greenhouse gas emissions (Davis and Caldeira 2010; Peters et al. 2011; Skelton 2013). To date, emissions are most frequently attributed to the national territory from which they are released, as reflected in production-based accounting of emissions (PBA) conducted in accordance with the United Nations Framework Convention on Climate Change (United Nations 1992; Davis and Caldeira 2010).

In this regard, a long-standing concern is that countries could meet their commitments to reduce their territorial emissions by shifting production of carbon-intensive goods and services without reducing – or even increasing - global emissions (Kuik and Gerlagh 2003; Dechezleprêtre and Sato 2017). For this reason, it has been argued that the responsibility for emissions should be attributed to consumers as, for instance, expressed by Davis and Caldeira (2010): “It is intuitive that individuals who benefit from a process should bear some responsibility for the associated emissions […]. Yet, national inventories such as those conducted annually by parties to the United Nations Framework Convention on Climate Change […] account for only those emissions produced within sovereign territories […], ignoring the benefit conveyed to consumers through international trade”.

In order to address this shortcoming in emission accounting, some authors have proposed consumption-based emission accounting (CBA), which measures the level of emissions generated to meet domestic consumption (Davis and Caldeira 2010; Peters et al. 2011; Atkinson et al. 2011). This approach is increasingly applied in policy analysis (Mehling, van Asselt, and Droege 2018) and is prominent in the latest IPCC Assessment report (IPCC 2014) as well as the annual Carbon Budgets published by the Global Carbon Project (Global Carbon Project 2019). However, by focusing exclusively on the consumption side, CBA has been criticized as being one-sided, as it fails to take into account efforts to reduce emissions in the export sector and neglects the fact that producers also benefit from generating emissions (Jakob and Marschinski 2012; Jakob, Steckel, and Edenhofer 2014; Rodrigues and Domingos 2008). For this reason, an appropriate account of responsibility for trade-related emissions needs to reflect the associated benefits accruing over the entire value chain, ranging from the extraction of fossil fuels to final consumption (Tukker, Pollitt, and Henkemans 2020).

Our paper contributes to the literature by proposing a novel scheme to share responsibility for trade-related emissions between producers and consumers based on the economic benefits they derive from the release of GHG emissions to the atmosphere.

This paper proceeds as follows. Section 2 reviews the literature. Section 3 presents the economic theory behind our proposed accounting scheme. Section 4 describes the data and numerical methods used for our empirical application. Section 5 discusses the results. Section 6 concludes.

2. Literature Review

Some authors have proposed sharing responsibility for emissions along the value chain according to the value added at each production step (Lenzen et al. 2007; Piñero et al. 2019) or the income generated in the form of wages and capital return (Marques et al. 2012; Liang et al. 2017). Some have argued that producers should be held responsible for emissions generated through their products (Lenzen and Murray 2010) or through economic activities under their control (Ortiz, López, and Cadarso 2020). While these approaches allow for a more fine-grained understanding of the role of intermediary industries, they do not take into account the benefits accruing to final consumers. A few approaches explicitly consider how responsibility for trade-related emissions could be shared between consumers and producers. These include proposals to use a predetermined sharing rule (Ferng 2003; Gallego and Lenzen 2005; Lenzen et al. 2007). A more recent approach suggests the use of ’valued added’ as a measure of producers responsibility and material throughput as a measure for consumers responsibility (Csutora and Vetőné mózner 2014). Besides being designed for single region input-output systems and their sensitivity to changes in the material throughput coefficients, measures employed in existing studies on the sharing of responsibility for emissions between producers and consumers tend to be *ad hoc* rather than relying on a solid theoretical foundation.

By contrast, the approach presented in this paper uses a straightforward measure of economic benefits that we derive from economic theory to assign responsibility for trade-related emissions to different world regions in a multi-regional input-output model. We propose to divide responsibility for trade-related emissions between producers and consumers, relative to the economic surplus they derive from not being required to pay the economic costs associated with greenhouse gas emissions. Our numerical application compares this ‘Economic Benefit Shared Responsibility’ (EBSR) scheme to conventional PBA and CBA approaches.

3. Sharing responsibility for emissions between producers and consumers based on economic benefits

This paper proposes a novel approach to the allocation of responsibility for trade-related emissions between consumers and producers. To our knowledge it is the first model that exploits economic theory, artificially creating a ’what-if’ counterfactual. Our EBSR scheme assigns responsibility for trade-related emissions in proportion to the economic benefits derived by producers and consumers from releasing emissions to the atmosphere when not being required to pay for their associated social cost. As counterfactual, we employ a scenario in which a global carbon price, which has frequently been highlighted as the economically optimal solution to address climate change (Edenhofer et al. 2015), is in place. EBSR thus distributes responsibility for trade-related emissions relative to economic costs that would accrue to producers and consumers, respectively, if such a global carbon price were in place.

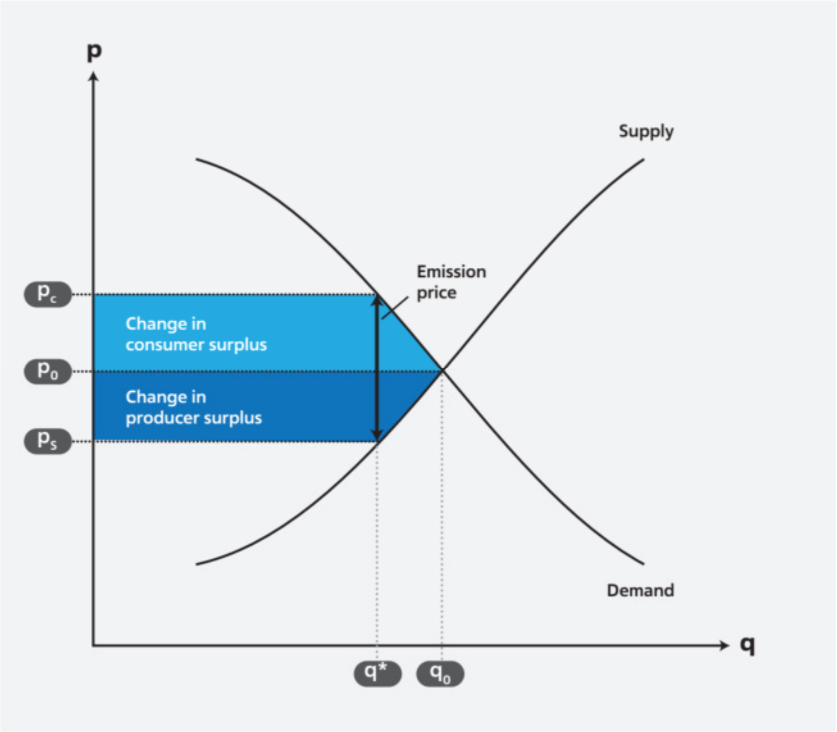

Figure 1: A (counterfactual) price on greenhouse gas emissions would reduce the economic surplus of producers (dark areas) as well as consumers (light area). EBSR employs the relative magnitude of these surpluses to divide responsibility for trade-related emissions to producers and consumers.

The economic intuition behind this approach is visualized in Figure 1. In a setting in which neither producers nor consumers have to pay the social costs of greenhouse gas emissions, the interplay of supply of exports and demand for imports would result in equilibrium price and quantity p_0 and q_0. If, however, climate damages were correctly accounted for, for instance by means of a global carbon price (Edenhofer et al. 2015), producers would receive a lower price p_s, and consumers would pay a higher price p_c, compared to the market equilibrium without environmental regulation (Fullerton and Muehlegger 2019). This would reduce their benefits, which are denoted as producer and consumer surplus, respectively, in two ways: first, by foregoing the benefits of emissions that correspond to the difference between q_0 and q^*, and second, by having to pay for those emissions that would still be generated with environmental regulation in place. This implies that both producers and consumers currently benefit to a certain extent from non-existing environmental regulations. This perspective can be generalized to all cases in which carbon prices that are below the social costs of carbon are in place (see Section 6 and SI). EBSR then fulfills the principle of 'additivity', which requires the sum of all national EBSR emissions to equal global emissions (Kander et al. 2015). By contrast, there seems to be no obvious need to account for emissions that are appropriately priced.

The EBSR approach we propose is based on the idea of assigning emissions in proportion to the benefits that producers and consumers, respectively, derive from emissions without having to pay their associated social cost. It illustrates that both exporters and importers benefit from the emissions that are released in one country to meet consumption in another country. We derive simple analytical expressions for the change in consumer and producer surplus that would occur – or, vice versa, the benefits that currently accrue to them due to the lack of environmental regulation.

Assuming isoelastic supply and demand functions with elasticities σ and δ, we can choose units such that we can – without loss of generality – write:

$$q_s = p_s^{\sigma},\ q_d = p_d^{\delta} \tag{1}$$

Then, in the unregulated case in which emissions can be generated free of charge, prices received by producers are equal to prices paid by consumers (i.e. $p_d = p_s$). This directly yields the equilibrium price $p_0 = 1$.

Now, let us consider the case in which the social costs of climate change are, at least to some extent, internalized by a carbon price T^*. Such a carbon price T would translate into a relative price increase, depending on the relative carbon content, which can be expressed as a gap t between prices paid by consumers and received by producers:

$$p_d = (1+t)p_s \tag{2}$$

Please note that our analysis does not presuppose that the optimal carbon price is imposed, rather it applies at any price level.

Equilibrium is then simply determined by equating supply and demand ($q_s = q_d$). This yields the following expression for producer and consumer prices:

$$p_s = (1+t)^{\delta/(\sigma-\delta)}\,,\ p_d = (1+t)^{\sigma/(\sigma-\delta)} \tag{3}$$

The change in producer surplus between the no tax and the tax scenarios can then be expressed as:

$$\Delta PR = \int_{p_s}^{p_0} p^\sigma dp = \frac{1}{(1+\sigma)}\left[1-(1+t)^{\delta(1+\sigma)/(\sigma-\delta)}\right] \tag{4}$$

Likewise, the change in consumer surplus between the two scenarios is:

$$\Delta CR = \int_{p_0}^{p_d} p^\delta dp = \frac{1}{(1+\delta)}\left[(1+t)^{\sigma(1+\delta)/(\sigma-\delta)}-1\right] \tag{5}$$

These expressions allow us to assess the division of responsibility for emissions in trade based on economic theory. They confirm the intuition that producers' and consumers' benefits reduce with an increase in price elasticity (i.e. the less they adjust quantities as a response to a price change). Economic theory highlights that those actors who are less likely to change their behavior as a result of regulation, i.e. display a lower 'elasticity' (which, in Figure 1, corresponds to steeper slope), derive a higher benefit from the absence of regulation (Fullerton and Muehlegger 2019). Hence, our approach assigns a higher share of bilateral trade-related emissions to the country with the lower elasticity of import or export, respectively. Countries with lower import or export elasticities can be regarded as being more dependent on foreign trade. Hence, they will be more affected by price changes than countries that can more easily adjust their production or consumption patterns. For the polar cases of totally inelastic supply (demand)

– that is, a vertical supply (demand) curve –responsibility for trade-related emissions is entirely assigned to exporters (importers). EBSR is then equivalent to PBA (CBA).

4. Data and Numerical Implementation

For each bilateral trade relation (BTR), we first identify the value added in one country, eventually consumed in the other country, as well as the associated CO_2 emissions. Combining this information with the respective export and import elasticities allows us to assess how consumers' and producers' economic surplus would change if the social costs of emissions were appropriately reflected in market prices.

Data

To adequately consider complex economic production chains, we use the World-Input-Output Database (WIOD) (Timmer et al. 2015; Corsatea et al. 2019). Using WIOD for the year 2014, we derive highly detailed bilateral trade flows, i.e. the sum of all value added being produced in one region and consumed in the other as directed bilateral trade flow, between the 44 regions included, considering 56 sectors.

WIOD includes the EU 28 countries as well as major economies, including most OECD countries (Australia, Canada, Japan, South Korea, Mexico, United States), newly industrializing economies, (i.e., Brazil, China, Indonesia, India, Turkey, Taiwan and Russia), and an aggregated residual region referred to as the "Rest of the World" (RoW). Additionally, WIOD provides detailed data on energy use and emitted greenhouse gas emissions, which allows us to calculate the carbon intensity of representative goods for bilateral trade relations.

To project the impacts of a global carbon tax on producers and consumer surplus and construct the counterfactual, we take country specific export and import elasticity estimates from the literature (see Tokarick (2014) and Supplementary Table S5).

Calculating carbon footprints

Standardized MRIO data accounts for a specific numbers of regions n and sectors m. They consist of an inter-industry flow matrix $Z \in \mathbb{R}^{(m \cdot n)\times(m \cdot n)}$ and a final demand vector $Y \in \mathbb{R}^{m \cdot n \times n}$, see e.g. (Miller and Blair 2009). Entries $z_{r_1 s_1}^{r_2 s_2}$ of Z reflect the total monetary value (in USD) of flows from sector $s_1$in region r_1 to sector s_2 in region r_2, with $r_1, r_2 \in R = \{1, \dots, n\}$ and $s_1, s_2 \in S = \{1, \dots, m\}$. Analogously, $y_{r_1, s_1}^{r_2}$ represents the sum of all monetary flows from sector s_1 of region r_1 into final demand of region r_2.

These can be used to calculate the total output vector $O \in \mathbb{R}^{m \times n}$, with entries $o_{r_1,s_1} = \sum_s \sum_r (z^{r,s}_{r_1 s_1}) + \sum_r y^{r}_{r_1,s_1}$. The total input vector I results as $i_{r_1,s_1} = \sum_s \sum_r (z^{r_1 s_1}_{r,s})$. Hence, $O - I$ represents total sectoral value-added VAD. By $A \in \mathbb{R}^{(m \cdot n)\times(m \cdot n)}$ we denote the technology matrix, with entries $a^{r_2 s_2}_{r_1 s_1}$=$z^{r_2 s_2}_{r_1 s_1}/o_{r_2,s_2}$. These describe the amount of each input that is necessary to produce one unit of output.

The Leontief inverse L, which accounts for all pre-products that have been used at some stage during production is calculated as $L = (I - A)^{-1}$. Let $CO_{2_{r1,s1}}$ be the total direct CO₂ emissions that have been released in sector s_1 of region r_1. The carbon intensity $CI_{r1,s1}$ then results as $CO_{2_{r1,s1}}/o_{r_1,s_1}$.

Let $BTR^{r_2}_{r_1}$ be the sum of value added of production steps that have eventually been undertaken in r_1 to serve final consumption in r_2. These can then be calculated as

$$BTR^{r_2}_{r_1} = \sum_r \sum_{s*} \sum_s \left(y^{r_2}_{r,s} \cdot l^{r,s}_{r_1,s*} \cdot vad^{s*}_{r_1}\right) \tag{6}$$

The associated emissions that are virtually contained within these flows $CO2^{r_2}_{r_1}$ are

$$CO2^{r_2}_{r_1} = \sum_r \sum_{s*} \sum_s \left(y^{r_2}_{r,s} \cdot l^{r,s}_{r_1,s*} \cdot CI^{s*}_{r_1}\right) \tag{7}$$

Evaluating the counterfactual

Our approach to assess the distributed responsibility for emissions in trade between producer and consumer requires only three parameters, namely the carbon price and elasticities of supply and demand. For the former, we assume a carbon price *T* of 50 USD/t of CO₂, in the range of what has been proposed to meet the climate targets enshrined in the Paris Agreement (Carbon Pricing Leadership Coalition 2017), see Supplementary Figure S6 for alternative specifications with carbon prices of USD 10, USD 100 and USD 1000 per ton of CO₂. The respective share of trade-related emissions assigned to the importing (exporting) country is given by the size of the light (dark) area relative to the total area in Figure 1.

The relative tax level $\boldsymbol{t}$ for a BTR of two regions then results as $t^{r_2}_{r_1} = {CO2^{r_2}_{r_1}}\Big/{BTR^{r_2}_{r_1}} \cdot T$. This expression considers the Normalized Net Carbon Content (NNCC), a measure which refers to the carbon content per one USD of VAD, which has been introduced by Ward et al. (2019) . Region specific import- ($\boldsymbol{\delta}$) and export ($\boldsymbol{\sigma}$) elasticity estimates are taken from recent literature (Tokarick 2014). We assign responsibility for traded emission in proportion to the distribution of the economics surplus without a price on carbon. That is, the producers' share of trade-related emissions is given by $s_{r_1} = \Delta PR/(\Delta PR + \Delta CR)$, the consumers' share by $s_{r_2} = \Delta CR/(\Delta PR + \Delta CR)$. Hence, producer and consumer responsibility R_{r_1} and R_{r_2}, respectively are:

$$R_{r_1} = s_{r_1} \cdot CO2_{r_1}^{r_2} \text{ and } R_{r_2} = s_{r_2} \cdot CO2_{r_1}^{r_2} \qquad (8)$$

5. Results

Figure 2 maps the emissions associated with bilateral trade-flows between the five regions with the highest trade-related emissions (i.e. the sum of export- and import-related emissions). These are China, the US, India, Russia and the EU28. Exports from these five regions are associated with emissions of 4.22 $GtCO_2$. Each arrow is divided into two segments denoting the emissions of the respective trade flow that are assigned to the exporting (dark) and importing (light) region under EBSR. For each region, blue bars denote the emissions that have been released in other countries to produce this region's imports, and red bars represent all emissions released in this country to produce exports to other countries. For both bars, dark areas denote the share of import- and export-related emissions, respectively, that are assigned to the region. Whereas under a production-based (consumption-based) perspective, a region is responsible for all emissions related to its exports (imports) as indicated by the red (blue) bars, our shared responsibility perspectives assigns responsibility as given by the dark-shaded areas of both bars. Bilateral trade flows between regions are depicted by arrows, which indicate how the responsibility for the associated emissions is divided between the respective exporting (dark) and importing region (light).

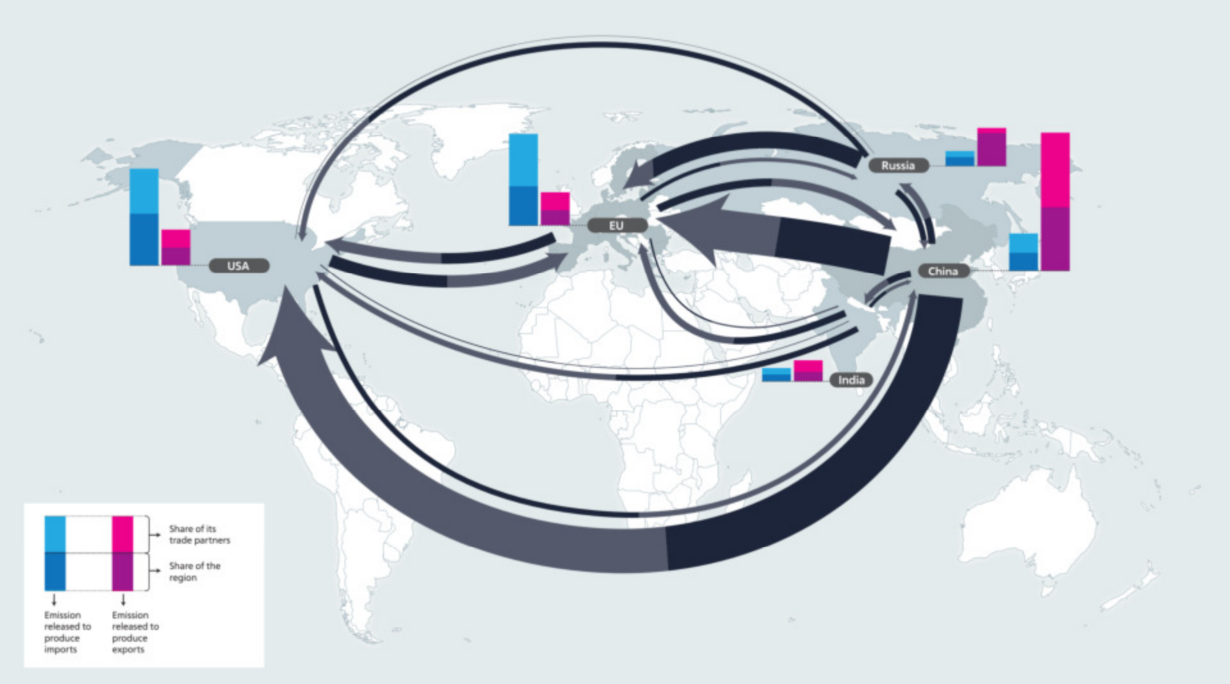

Figure 2: Responsibility for trade-related greenhouse gas emissions under the EBSR scheme. Arrows denote responsibility for emissions assigned to exporters (dark areas) and importers (light areas), respectively. Blue and red bars show responsibility for imports and exports, respectively. Results are shown for the five regions featuring the highest trade-related emissions (sum of emissions released for the region's imports and exports).

Globally, the highest trade-related emissions are found for China, whose exports correspond to more emissions than those of the exports by the US, EU, Russia and India taken together. Out of a total of 2.16 $GtCO_2$ that are released to produce Chinese exports, 375 $MtCO_2$ are generated for exports to the US, and 342 $MtCO_2$ for exports to the EU. Under EBSR, 56% of emissions related to Chinese exports to the US are assigned to the US, and 44% to China. For China-EU trade, the respective figures are 53% and 47%. Overall, 46% of all emissions related to Chinese exports are assigned to China, and 54% to its trade partners.

Russia constitutes another important source of export-related emissions of about 547 $MtCO_2$, a large share of which (145 $MtCO_2$) are targeted at the EU. Interestingly, under EBSR the lion's share of these emissions, namely 87%, accrue to Russia. Similar numbers are found for Russia's trade with China (86%), as well as with the US and India (85% for both partners). This is explained by Russia's low export elasticity of 0.22, the lowest value for all regions in our sample, which might be due the country's dependence on revenues from natural resource exports.

Regarding trade between the EU and the US, exports from the EU to the US account for about 15% of the EU total export-related emissions of 678 $MtCO_2$, that is, 105 $MtCO_2$. The EBSR approach assigns 54% of these emissions to the US, and 46% to the EU. In the other direction, exports from the US to the EU correspond to 90 $MtCO_2$, about a fifth of total US export-related emissions of 453 $MtCO_2$. Under EBSR, emissions related to US exports to the EU are shared evenly between both regions, that is, 50% each.

Finally, a substantial share of India's export-related emissions of 386 $MtCO_2$ is released to produce exports to the EU and the US, namely 58 $MtCO_2$ and 52 $MtCO_2$, respectively. The EBSR scheme attributes 47% of emissions released for exports to the EU, and 44% of the emissions released for exports to the US, to India. It is interesting to note that for India the highest share of import-related emissions come from China, amounting to 56 $MtCO_2$. Of these, EBSR attributes 56% to India (and hence 44% to China).

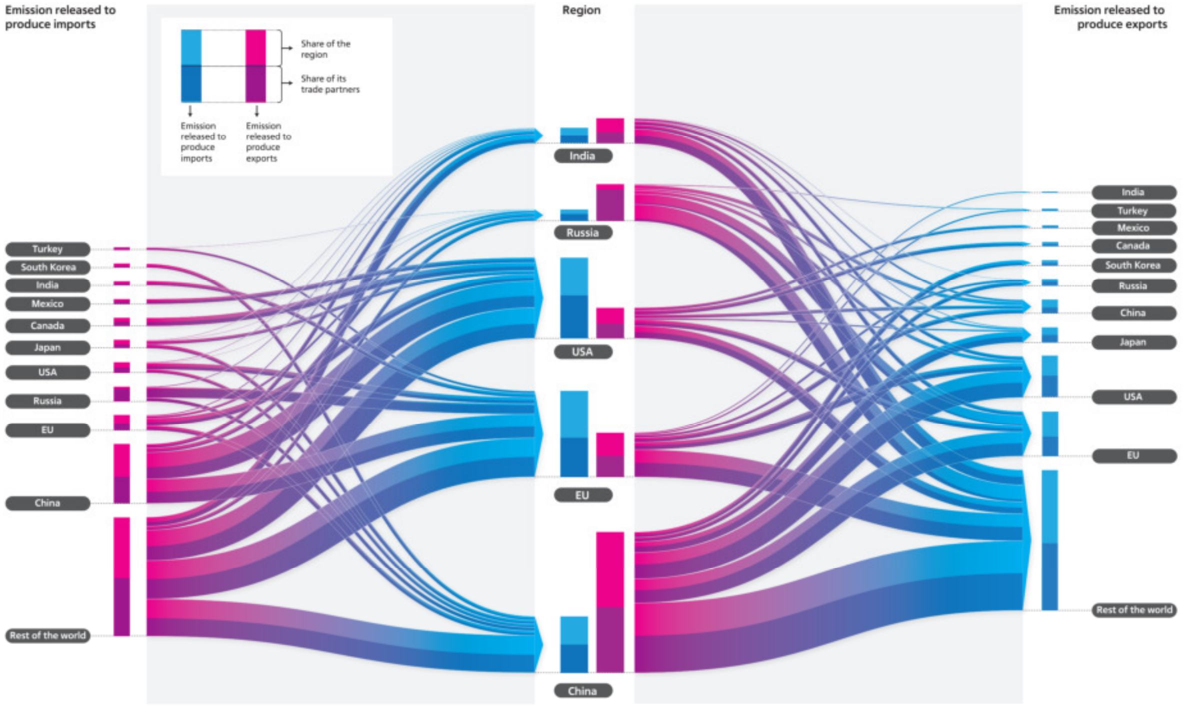

Figure 3: Flows of import- and export-related emissions between the five main regions and their most important trade partners. Blue and red bars show responsibility for imports and exports, respectively. Flows include all countries that are among the top-five recipients of export-related emissions from China, US, EU, India or Russia as well as the aggregate region 'Rest of the World'.

Figure 3 provides additional detail by including all countries that are among the top five recipients of export-related emissions for at least one of the regions displayed in Figure 2 (that is, China, US, EU, India and Russia), as well as the aggregate region 'Rest of the World' (which consists of all other countries). This aggregate region accounts for 44% of all export-related and 47% of all import-related emissions of the five regions displayed in the center of the figure.

The US, Canada and Mexico are trade partners responsible for substantial emission flows. For instance, with emissions of 114 $MtCO_2$, US imports from Canada constitute a larger emission source than imports from the EU (105 $MtCO_2$). For China, South Korea is the fourth largest destination of export-related emissions, even though it accounts for less than 4% of the total. Japan is ranked third for China, fourth for India and Russia, and fifth for the US. Finally, Turkey is the fifth largest destination for Russia as well as the EU.

Figure 3 also provides an insight into why EBSR may provide a very different picture of responsibility for trade-related emissions than either PBA or CBA. For instance, China's emissions under EBSR are lower than under PBA, but higher than under CBA. This can be explained by the fact that China's total trade-related emissions (for imports as well as exports) are dominated by emissions that are released to produce exports. Whereas PBA (CBA) attributes full (no) responsibility for export-related emissions to China, EBSR strikes a middle ground by attributing a fraction of these emissions to China. By contrast, for the US and EU, EBSR yields higher emissions than PBA, but lower ones than CBA. For both regions trade-related emissions are dominated by imports. Whereas with PBA (CBA), these emissions would not be attributed at all (fully), EBSR instead attributes a proportion to the importing region. Finally, for Russia, for which trade-related emissions are dominated by exports, it is interesting to note that EBSR would not only yield higher responsibility than CBA, but that EBSR would be practically identical to PBA. The reason for this is that Russia's low export elasticity means that the country is attributed the greatest share of its export-related emissions (86%) (note that under PBA, this share would be 100%). The remaining 14% of Russia's export-related emissions that are attributed to the country's trade partners are almost exactly matched by the responsibility for import-related emissions assigned to Russia under EBSR.

Based on these results, Figure 4 compares responsibility for trade-related emissions under EBSR, CBA and PBA in more detail on the level of individual countries. To ensure comparability between countries with very different emission levels, the figure indicates the percentage by which traditional PBA would be adjusted by considering trade-related emissions by either a consumption-based (CBA) or a shared responsibility (EBSR) perspective (i.e. the 'emission trade balance'). For most countries we find that EBSR yields an outcome between CBA and PBA (note that PBA corresponds to a value of zero, as no adjustment is required). The magnitude of this adjustment, however, differs widely across countries. For instance, whereas EBSR is quite close to CBA for Australia, Brazil, the Czech Republic, Spain and Mexico, it is close to PBA for countries including Belgium, Bulgaria, Croatia Denmark, Germany, Finland, Romania and Russia. Furthermore, depending on the relationship between export- and import-related emissions, as well as the respective shares that are attributed to exporters and importers, EBSR can also yield higher absolute numbers than CBA, which is the case for Indonesia, South Korea, Norway, Turkey, and Taiwan. Finally, there are also cases in which the EBSR and CBA trade balance have opposite signs. This can, for instance, occur if a country has high (low) elasticities for both imports and exports, generating a relatively small (high) EBSR attribution of trade-related emissions. We observe outcomes in which EBSR and CBA work in different directions for Canada, Hungary, Malta, the Netherlands as well as the 'Rest of the World' aggregate.

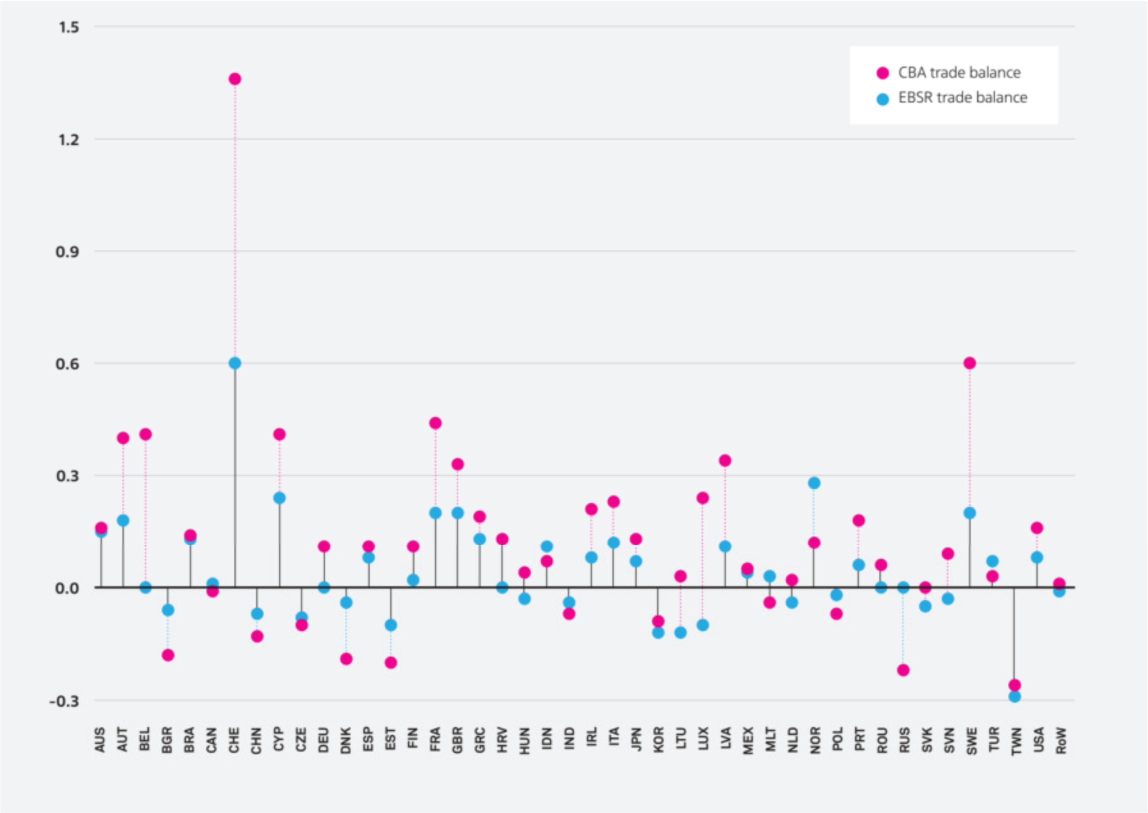

Figure 4: Percentage by which PBA is adjusted if trade-related emissions are accounted based on consumer responsibility (CBA) or economic benefit shared responsibility (EBSR).

6. **Discussion and Conclusions**

This paper proposes a novel ‘Economic Benefit Shared Responsibility’ (EBSR) scheme to account for carbon emissions that are released to the atmosphere to produce traded goods and services. We highlight that responsibility for trade-related emissions cannot be attributed exclusively to producers or consumers but needs to be shared between them. We propose the use of the economic benefits producers and consumers derive from being able to generate emissions free of charge, respectively, as a measure of how to share responsibility for trade-related emissions. Based on the real-world data that are available, we demonstrate how this approach could be implemented.

This analysis is subject to several limitations. Perhaps most importantly, it assumes that production structures and technologies are fixed, such that an emission price would be fully passed through to consumers. In our model, producers and consumers can only react to this price change by adjusting quantities, but not by changing technologies or substituting other goods. Moreover, we do not account for the fact that even though to date most emissions are indeed unpriced, some regions have significant carbon prices in place (OECD 2018). Conceptually, our analysis can straightforwardly be extended to account for all emissions that are priced below the social optimum (see SI for details). The most serious challenge in this regard would lie in the fact that within individual countries, carbon prices often display large variation across economic sectors. Hence, considering existing carbon prices would not only require reliable estimates of sectoral carbon prices for all countries, but also a sectoral analysis of trade flows, as discussed below. To explore how existing carbon pricing could affect our findings, we carry out our analysis for regionally differentiated carbon prices that would be compatible with the 2°C temperature target. These prices are generated with the integrated assessment model MESSAGE under the assumptions of the shared socioeconomic pathway scenario 2 (Fricko et al. 2017), which assumes technological and socio-economic developments roughly in line with historic trends. Using the carbon prices projected for the year 2030 for the five regions with the highest trade-related emission displayed in Figure 2 hardly changes our results (see supplementary table S1). Finally, our assessment of how imports and exports would respond to such an emission price is based on available estimates of elasticities of export and import for individual countries. These estimates hide substantial details of sector-specific and bilateral trade relations (Cadarso et al. 2012). A more fine-grained analysis would require thousands of country- and sector-specific trade elasticities, which, to our knowledge, are not available. Future research could extend our analysis by estimating these elasticities and assess producers’ as well as consumers’ benefits from below-optimal carbon prices on a sectoral level based on a consistent set of trade data. For the reasons outlined above, our analysis should first and foremost be regarded as a conceptual contribution, illustrated with available data. Nevertheless, by going beyond a one-sided focus on producers or consumers, the approach presented in this paper could provide a basis for a more nuanced debate regarding the responsibility for trade-related emissions.

Our approach assesses the counterfactual scenario in which the social costs of greenhouse gas emissions are borne by consumers and producers by means of a carbon price. By contrast, some recent contributions apply alternative approaches, based on the counterfactual perspective of the absence of trade. These schemes evaluate a country's imports and exports either relative to the average global emission intensity for the respective goods and services (Kander et al. 2015; Jiborn et al. 2018; Baumert et al. 2019), or from the perspective of how a country's trade specialization contributes to meeting global consumption in a carbon-efficient manner (Dietzenbacher, Cazcarro, and Arto 2020). In this way, reductions in global emission resulting from cleaner exports can be accounted for (in contrast to CBA, which attributes all export-related emissions to trade partners). Combining such schemes with accounting schemes for shared producer and consumer responsibility in dashboards for 'multiple carbon accounting' (Steininger et al. 2016) could help to establish a comprehensive picture of the responsibility for trade-related emissions.

Data and material availability

All data necessary to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Information. Additional data related to this paper may be requested from the authors.

Competing interests

The authors declare that they have no competing interests.

References

Atkinson, Giles, Kirk Hamilton, Giovanni Ruta, and Dominique Van Der Mensbrugghe. 2011. “Trade in ‘virtual Carbon’: Empirical Results and Implications for Policy.” *Global Environmental Change* 21 (2): 563–74. https://doi.org/10.1016/j.gloenvcha.2010.11.009.

Baldwin, Richard E. 2009. “The Spoke Trap: Hub and Spoke Bilateralism in East Asia.” *Swiss National Centre of Competence in Research Working Paper* 2009/28.

Baumert, Nicolai, Astrid Kander, Magnus Jiborn, Viktoras Kulionis, and Tobias Nielsen. 2019. “Global Outsourcing of Carbon Emissions 1995–2009: A Reassessment.” *Environmental Science & Policy* 92 (February): 228–36. https://doi.org/10.1016/j.envsci.2018.10.010.

Cadarso, María-Ángeles, Luis-Antonio López, Nuria Gómez, and María-Ángeles Tobarra. 2012. “International Trade and Shared Environmental Responsibility by Sector. An Application to the Spanish Economy.” *Ecological Economics* 83 (November): 221–35. https://doi.org/10.1016/j.ecolecon.2012.05.009.

Carbon Pricing Leadership Coalition. 2017. “Report of the High-Level Commission on Carbon Prices.” https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices/.

Corsatea, T.D., S. Lindner, I. Arto, M.V. Román, J.M. Rueda-Cantuche, A. Velázquez Afonso, A. Amores, and F. Neuwahl. 2019. “World Input-Output Database Environmental Accounts. Update 2000-2016.” Publications Office of the European Union, Luxembourg. doi:10.2791/947252.

Csutora, Maria, and Zsófia Vetőné mózner. 2014. “Proposing a Beneficiary-Based Shared Responsibility Approach for Calculating National Carbon Accounts during the Post-Kyoto Era.” *Climate Policy* 14 (5): 599–616. https://doi.org/10.1080/14693062.2014.905442.

Davis, S. J., and K. Caldeira. 2010. “Consumption-Based Accounting of CO2 Emissions.” *Proceedings of the National Academy of Sciences* 107 (12): 5687–92. https://doi.org/10.1073/pnas.0906974107.

Dechezleprêtre, Antoine, and Misato Sato. 2017. “The Impacts of Environmental Regulations on Competitiveness.” *Review of Environmental Economics and Policy* 11 (2): 183–206.

Dietzenbacher, Erik, Ignacio Cazcarro, and Iñaki Arto. 2020. “Towards a More Effective Climate Policy on International Trade.” *Nature Communications* 11 (1). https://doi.org/10.1038/s41467-020-14837-5.

Edenhofer, Ottmar, Michael Jakob, Felix Creutzig, Christian Flachsland, Sabine Fuss, Martin Kowarsch, Kai Lessmann, Linus Mattauch, Jan Siegmeier, and Jan Christoph Steckel. 2015. “Closing the Emission Price Gap.” *Global Environmental Change* 31: 132–43. https://doi.org/10.1016/j.gloenvcha.2015.01.003.

Ferng, Jiun-Jiun. 2003. “Allocating the Responsibility of CO2 over-Emissions from the Perspectives of Benefit Principle and Ecological Deficit.” *Ecological Economics* 46: 121–41. https://doi.org/10.1016/S0921-8009(03)00104-6.

Fricko, Oliver, Petr Havlik, Joeri Rogelj, Zbigniew Klimont, Mykola Gusti, Nils Johnson, Peter Kolp, et al. 2017. “The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century.” *Global Environmental Change* 42 (January): 251–67. https://doi.org/10.1016/j.gloenvcha.2016.06.004.

Fullerton, Don, and Erich Muehlegger. 2019. “Who Bears the Economic Burdens of Environmental Regulations?” *Review of Environmental Economics and Policy* 13 (1): 62–82. https://doi.org/10.1093/reep/rey023.

Gallego, Blanca, and Manfred Lenzen. 2005. “A Consistent Input–output Formulation of Shared Producer and Consumer Responsibility.” *Economic Systems Research* 17 (4): 365–91. https://doi.org/10.1080/09535310500283492.

Global Carbon Project. 2019. *Supplemental Data of Global Carbon Budget 2019 (Version 1.0) [Data Set].* https://www.globalcarbonproject.org/carbonbudget/19/data.htm.

Hummels, David. 2007. "Transportation Costs and International Trade in the Second Era of Globalization." *Journal of Economic Perspectives* 21 (3): 131–54.

IPCC. 2014. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by Ottmar Edenhofer, Ramón Pichs-Madruga, Youba Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. http://mitigation2014.org.

Jakob, Michael, and Robert Marschinski. 2012. "Interpreting Trade-Related CO2 Emission Transfers." *Nature Climate Change* 3 (1): 19–23. https://doi.org/10.1038/nclimate1630.

Jakob, Michael, Jan Christoph Steckel, and Ottmar Edenhofer. 2014. "Consumption- Versus Production-Based Emission Policies." *Annual Review of Resource Economics* 6 (1): 297–318. https://doi.org/10.1146/annurev-resource-100913-012342.

Jiborn, Magnus, Astrid Kander, Viktoras Kulionis, Hana Nielsen, and Daniel D. Moran. 2018. "Decoupling or Delusion? Measuring Emissions Displacement in Foreign Trade." *Global Environmental Change* 49 (March): 27–34. https://doi.org/10.1016/j.gloenvcha.2017.12.006.

Kander, Astrid, Magnus Jiborn, Daniel D. Moran, and Thomas O. Wiedmann. 2015. "National Greenhouse-Gas Accounting for Effective Climate Policy on International Trade." *Nature Clim. Change* 5 (5): 431–35.

Kuik, Onno, and Reyer Gerlagh. 2003. "The Effect of Trade Liberalization on Carbon Leak-Age under the Kyoto Protocol: Experiments with GTAP-E." *The Energy Journal* 24: 97–120.

Lenzen, Manfred, and Joy Murray. 2010. "Conceptualising Environmental Responsibility." *Ecological Economics* 70 (2): 261–70. https://doi.org/10.1016/j.ecolecon.2010.04.005.

Lenzen, Manfred, Joy Murray, Fabian Sack, and Thomas Wiedmann. 2007. "Shared Producer and Consumer Responsibility — Theory and Practice." *Ecological Economics* 61 (1): 27–42.

Liang, Sai, Shen Qu, Zeqi Zhu, Dabo Guan, and Ming Xu. 2017. "Income-Based Greenhouse Gas Emissions of Nations." *Environmental Science & Technology* 51 (1): 346–55. https://doi.org/10.1021/acs.est.6b02510.

Marques, Alexandra, Joao Rodrigues, Manfred Lenzen, and Tiago Domingos. 2012. "Income-Based Environmental Responsibility." *Ecological Economics* 84: 57–65. https://doi.org/10.1016/j.ecolecon.2012.09.010.

Mehling, Michael A., Harro van Asselt, and Susanne Droege. 2018. "Beat Protectionism and Emissions at a Stroke." *Nature* 559: 321–24.

Miller, Ronald E., and Peter D. Blair. 2009. *Input-Output Analysis*. Second Edition. Cambridge University Press.

OECD. 2018. "Effective Carbon Rates 2018." https://www.oecd.org/tax/tax-policy/effective-carbon-rates-2018-brochure.pdf.

Ortiz, Mateo, Luis-Antonio López, and María-Ángeles Cadarso. 2020. "EU Carbon Emissions by Multinational Enterprises under Control-Based Accounting." *Resources, Conservation and Recycling* 163 (December): 105104. https://doi.org/10.1016/j.resconrec.2020.105104.

Peters, Glen P., Jan C. Minx, Christopher L. Weber, and Ottmar Edenhofer. 2011. "Growth in Emission Transfers via International Trade from 1990 to 2008." *Proceedings of the National Academy of Sciences* 108 (21): 8903–8908.

Piñero, Pablo, Martin Bruckner, Hanspeter Wieland, Eva Pongrácz, and Stefan Giljum. 2019. "The Raw Material Basis of Global Value Chains: Allocating Environmental Responsibility Based on Value Generation." *Economic Systems Research* 31 (2): 206–27. https://doi.org/10.1080/09535314.2018.1536038.

Rodrigues, Joao, and Tiago Domingos. 2008. “Consumer and Producer Environmental Responsibility: Comparing Two Approaches.” *Ecological Economics* 66 (2–3): 533–46. https://doi.org/10.1016/j.ecolecon.2007.12.010.

Skelton, Andrew. 2013. “EU Corporate Action as a Driver for Global Emissions Abatement: A Structural Analysis of EU International Supply Chain Carbon Dioxide Emissions.” *Global Environmental Change* 23 (6): 1795–1806. https://doi.org/10.1016/j.gloenvcha.2013.07.024.

Steininger, Karl W., Christian Lininger, Lukas H. Meyer, Pablo Muñoz, and Thomas Schinko. 2016. “Multiple Carbon Accounting to Support Just and Effective Climate Policies.” *Nature Climate Change* 6 (1): 35–41. https://doi.org/10.1038/nclimate2867.

Timmer, Marcel, Erik Dietzenbacher, Bart Los, Robert Stehrer, and G. J. 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, Marcel, AA Erumban, Bart Los, Robert Stehrer, and Gaaitzen de Vries. 2014. “Slicing Up Global Value Chains.” *Journal of Economic Perspectives* 28 (2): 99–118.

Tokarick, Stephen. 2014. “A Method for Calculating Export Supply and Import Demand Elasticities.” *The Journal of International Trade & Economic Development* 23 (7): 1059–87. https://doi.org/10.1080/09638199.2014.920403.

Tukker, Arnold, Hector Pollitt, and Maurits Henkemans. 2020. “Consumption-Based Carbon Accounting: Sense and Sensibility.” *Climate Policy* 20 (sup1): S1–13. https://doi.org/10.1080/14693062.2020.1728208.

United Nations. 1992. “United Nations Framework Convention on Climate Change.” https://unfccc.int/resource/docs/convkp/conveng.pdf.

Ward, Hauke, Jan Christoph Steckel, and Michael Jakob. 2019. “How Global Climate Policy Could Affect Competitiveness.” *Energy Economics* 84 (October): 104549. https://doi.org/10.1016/j.eneco.2019.104549.