Interpreting CO_2 emission transfers via international trade

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Most industrialized countries are net importers of carbon emissions, i.e. they release fewer emissions for the production of their total *exported* goods and services than the amount generated (by their trading partners) for producing their total *imported* goods and services[1-8]. But what do such 'carbon trade deficits' imply in terms of global CO_2 emissions and the design of 'carbon trade policies'? Drawing on trade-theory, this *Perspective* argues that a deeper understanding of these observed net emission transfers is required to assess how international trade affects global emissions and proposes a method to disentangle the underlying determinants of net emission transfers.

A series of studies has recently measured the carbon content–or 'embodied' emissions–of international trade[1-8]. As one remarkable finding, imports to the United States were shown to contain on average 0.77 kg of CO_2 per dollar, whereas for its exports this number is only 0.49. For China the opposite is the case: 0.49 kg of CO_2 per dollar of imports stand against 2.18 for exports[1]. But does this means that China is specializing in the export of carbon-intensive goods, and vice versa the US in their import? This, in fact, would be the interpretation implied by a literal application of the so-called Heckscher-Ohlin theorem, one of the corner-stones of modern trade theory. It states that countries generally specialize in the export of goods whose production is intensive in factors – e.g. fossil fuels or carbon emissions – which they possess in relative abundance. Trade economists will also recall that this was the reasoning of Nobel-prize economist Leontief in 1953, when he employed his just developed input-output analysis to measure the labour and capital content of US output and foreign trade[9]. To his own surprise, he found US exports to be labour-intensive, with 182 person-years of labour 'embodied' in every million dollar of exports, but only 170 in imports. His counterintuitive result that the capital abundant US economy seemed to be specialized in supplying the world with labour-intensive goods became famously known as "Leontief paradox" and puzzled economists for decades, until it was eventually shown to be based on the incorrect application of trade theory[10].

Given this historical precedent, the question arises whether also in the above case of the different carbon intensities of trade found for the US and China an interpretation in terms of trade specialization patterns could lead to a “green Leontief paradox” (ref. 11). Moreover, while the presence of such a paradox might seem a trade-theoretic question of rather academic character, the observed imbalance of global carbon flows bears considerable political implications: for example, if the US and the EU are increasingly importing and consuming embodied emissions from developing countries, shouldn’t the former be held accountable for all emissions related to their consumption activities, including those emissions arising in the production of export goods in the latter (see, e.g., footnote 2 in ref. 5)? Technically speaking, such an approach could be implemented by what is called consumption-based accounting of carbon emissions[1,7], which is computed by adding to countries’ conventional production-based emissions (as currently computed under the UNFCCC methodology) their net transfers of emissions embodied in international trade (i.e. the carbon content of all imports minus that of all exports).

Clearly, consumption-based accounting provides a useful technique for determining the amount of emissions generated for the production of all goods and services that are consumed in a given country and, thereby, tracing the flow of emissions through the global economy. However, it constitutes first and foremost an accounting device[12]. As such it provides a necessary but not a sufficient informational basis for guiding the design of effective and fair policies aimed at reducing greenhouse gas emissions. For this purpose not only the carbon flows itself but also their underlying determinants must be understood, so as to make it possible to assess how emissions would be affected by new policies. As we want to highlight in this *Perspective* (and will explain more in detail in the coming sections), before conclusions with regard to specialization patterns and causal relationships can be drawn, further analysis is required. That is, it would be misleading to view the net transfers of emissions computed by consumption-based accounting as the 'cause' of a net increase of emissions in the producing country, as the latter's emissions might actually be higher in the absence of these transfers. As a consequence, a policy of consumption-based emission pricing–which could be achieved by means of a full border tax adjustment[13]–will not necessarily decrease overall greenhouse gas emissions.

Determining countries' trade specialization

Just like in Leontief's initial reasoning, the empirical findings on industrialized countries' increasing imports of embodied carbon emissions from developing countries were interpreted in some media reactions as a sign that the former–instead of cleaning up their act–are in effect just off-shoring their CO_2–intensive activities to the latter. *The Economist*[14], for example, commented the results of Peters et al.[2] with: "Rich countries are outsourcing carbon-dioxide emissions". This view as an outsourcing dynamic that systematically displaces emission-intensive processes would imply–at least in the view of classical trade theory based on the notion of comparative advantage–a change in the international division of labour (i.e. specialization), with industrialized countries shifting away and developing countries, especially China, shifting towards the production of emission-intensive goods.

However, the methodological shortcoming in Leontief's original analysis[9] of the empirical data was identified by Leamer[10] who overturned the conclusion that the US was specialized in the production of labour-intensive goods (in reality the opposite was the case, just as expected). He showed that in order to obtain information on specialization, trade-theory requires comparing the factor content–e.g. embodied labour–of a country's exports with the average factor content of its total production, and not–as done by Leontief and for the computation of net transfers of embodied emissions–with the one of its imports. To see this, consider the example of two countries that are identical in all aspects except that one country, e.g. due to a higher share of coal in its energy mix, has a more carbon-intensive energy system (but identical energy prices). In this case, even the exchange of very similar or identical goods would result in one country displaying a deficit and the other a surplus of carbon emissions embodied in trade, though they might actually not be specialized at all (in the sense of a comparative advantage, i.e. a sectoral specialization).

As a consequence, the net transfer of any production factor contained in trade–including energy-related carbon inputs–cannot be used to directly draw conclusions with regard to patterns of trade specialization. Finding that one country is a net-exporter of embodied carbon *could* of course indicate a specialization in goods that are *per se* relatively carbon-intensive in their production; however, it could just as well be the result of a particularly inefficient use of this factor. More specifially, high carbon contents in a country's exports could stem from this country's high energy intensity (energy required to produce one dollar of GDP), or its fossil fuels intensive energy system (carbon per unit of energy), with nothing to guarantee that the carbon-intensity of non-export production is not even higher (see ref. 15).

Leamer's approach also avoids another problem: it is robust in the presence of unbalanced trade. In fact, with trade deficits and surpluses, even trade between two perfectly identical countries would generate a net flow of embodied emissions from one country to the other, obviously without any relevance for specialization patterns. Moreover, as an artefact of using factor trade balances, a country with a strong trade surplus can in theory become a net exporter of all production factors, implying a meaningless specialization in every sector.

To demonstrate the empirical relevance of these arguments, we take up the results on emission transfers provided by Davis and Caldeira[1] and carry out an exemplary decomposition of the carbon trade balances of the six largest exporters and importers of embodied emissions, as well as for the five largest observed bilateral emission transfers (i.e. the net emission transfer between two countries or regions), as shown in Figures 1 and 2, respectively. The employed refined Laspeyres index decomposition allows attributing net flows of embodied carbon to the following four factors: (i) trade balance, (ii) economy-wide energy-intensity, (iii) economy-wide carbon-intensity of energy, and (iv) trade specialization (see *Supplementary Information* for details).

The results in Figure 1 demonstrate that the relative importance of these factors greatly depends on which specific country is considered. For the US about 50% of its net carbon imports can be attributed to its trade deficit, whereas the influence of the trade balance is below or at 10% for China and France, and around 15% for Germany, Russia, and Japan. On the other hand, the carbon-intensity of the domestic energy system accounts for roughly 25% and 50% of the net carbon trade balance of China (high carbon intensity) and France (low carbon intensity), respectively, but is negligible for the other considered countries. Finally, a relative specialization of China on the export of carbon-intensive goods can indeed be confirmed, and likewise the opposite for the US, but it contributes only 29% to China's total observed carbon exports and 43% to US imports. Hence, we do not re-encounter Leontief's historical paradox in this analysis, as that would require net exporters of emissions like China to actually be specialized in the production of goods with a relatively low carbon intensity, which would show by a negative contribution for trade specialization. Yet, one should note that this outcome is avoided merely by chance and only for the few countries of this very exemplary analysis.

The analysis of the bilateral emission transfers (Figure 2) corroborates the main insight, namely that there is significant variation in the contributions and relative importance of different factors. For instance, their massive trade imbalance is the main driver–making up almost 45%–of the large observed net flow of carbon from China to the US, while China's specialization in carbon-intensive exports accounts for only about 20%. A qualitatively similar picture emerges for the China-Western Europe carbon transfer, although in this case the general trade deficit is smaller while the higher energy intensity of China's economy and its specialization carry more weight (around 30% each). The net flow between Russia and China is small in absolute terms, but still represents an interesting case: although Russia runs a trade surplus with China, is relatively more specialized on the export of carbon-intensive goods, and also has a more energy-intensive economy, the net carbon transfer still results to be negligible, only because China has an energy system that is overall much more carbon-intensive. Finally, the US would be a net-importer of carbon from both WEU and Japan, as it runs a trade deficit with both, were it not for the fact that its economy is more energy-intensive and more specialized on the export of carbon-intensive goods (and, in the US-WEU case, also displays a more carbon intensive energy system).

Trade's impact on emissions not straightforward

By boldly stating "West blamed for rapid increase in China's CO_2" and highlighting "the West's responsibility" since "the recent rise in China's carbon dioxide pollution is caused by the manufacturing of goods for other countries" *The Guardian*[16] advanced its interpretation of the results of Guan *et al.*[3]. Perhaps inspired by the notion of the ‘carbon footprint’ associated with individual consumers, this view is nevertheless misleading as it neglects the economy-wide impacts of consumption decisions on prices of goods and production factors, and the indirect effects resulting thereof. This may be justifiable at the level of an individual consumer, whose decisions have only negligible effects on the economy as a whole, but not at the level of entire countries, whose decisions to, e.g., reduce the import of carbon-intensive goods from China will have repercussions on world markets. As a consequence, the characterization of final consumers as 'responsible' and imported goods as the ‘cause’ for carbon emitted in the exporting country should not be regarded as an indication that in the absence of the cause–i.e. without the imports–total emissions in the exporting (developing) country would be lower and, conversely, that the emissions of the importing (industrialized) country appear lower “than if they had continued to produce these goods domestically” (ref. 5).

In trade theory, the question of the net effect of trade has been termed the “but-for” question[17]: what would global carbon emissions be *but for* the presence of foreign trade? Answering this counter-factual question is by no means trivial, since with differing factor productivities (i.e. the quantity of goods that can be produced with one unit of a certain input factor) across countries, one country’s exported goods might result in savings of an input factor in the importing country that exceeds the amount used for their production by the exporter. That is, assessing the net impact of trade on global emissions requires a broad ‘systemic’ view – what economists call a general-equilibrium approach (which e.g. captures the effect of changes in one market on all other markets).

More specifically, if a country *A* were to withdraw from trade, and instead rely entirely on domestic production to meet its consumption, two opposing effects should be expected on the emissions of its former trading partner, country *B*: for one, the latter would produce less of the goods it previously exported to *A*, causing a drop in its emissions. But the suspension of trade relations would also induce country *B* to produce more of the goods it had originally imported from country *A*, implying an increase in its emissions. Appropriately accounting for the impact of trade on emissions in country *B* therefore requires confronting the emissions arising from the production of country *B*'s exports with the emissions that have been avoided by means of imports from country *A*. In general the amount of emissions generated by substituting country *B*'s imports from *A* with domestically produced goods will differ from the amount of emissions that were formerly generated for their production in country *A* (except if some highly restrictive assumptions are met, as discussed further below). Hence, reducing net imports of embodied emissions in country *A* might either increase or decrease emissions in country *B*, and computing the net carbon trade balance does not reveal what country *B*'s emissions would be in the absence of trade (cf. ref. 18).

For example, think of country *A* as exporting energy-intensive heavy industry goods (such as cars or machinery) using relatively clean energy, while country *B* exports less energy-intensive light manufacturing goods (such as toys, electronic products, or textiles) but has a carbon-intensive energy mix. It is then perfectly conceivable that country *A*'s exports–despite their higher energy-intensity–display a lower carbon content than the exports of country *B*, such that country *A* is a net importer of carbon emissions. Yet, if country *A* were to withdraw from trade relations with country *B*, the latter would increasingly engage in heavy manufacturing domestically, with a resulting increase in emissions that could exceed the decrease in emissions stemming from a reduced production of light industry goods for export.

Furthermore, if net emission transfers were understood as causing a net increase in emissions in exporting countries, it would appear paradoxical that the emissions of countries which are found to be net exporters of carbon would actually stay the same or even increase if they were to withdraw from international trade and produce their current consumption domestically, as it indeed seems to be the case for China[8] and India[11], respectively. This also means that observing so-called 'weak' carbon leakage, i.e. increasing imports of embedded carbon by industrialized (Annex B of Kyoto Protocol) countries from developing (non-Annex B) countries[6], should not be interpreted as sufficient evidence that trade has resulted in a net increase of emissions in the latter (although this *could* of course be the case). For instance, one can easily imagine that ambitious climate policies in the EU would also decrease the emissions embedded in its exports. As a consequence, the EU's net imports of emissions could increase not because the production of carbon-intensive goods has been offshored, but simply because exports are now produced with a cleaner technology. Finally, if one country's net imports of embodied emissions cannot be regarded as the actual cause for emissions of the exporting country, it can also be questioned whether the consumption-based approach of attributing responsibility for imported emissions to consumers can be regarded as "a fairer method of allocating responsibility for GHGs" (ref. 4) than the current practice of production-based accounting.

Consumption-based pricing and carbon leakage

Because it ensures that consumers in developed countries bear the full costs for all of their consumption-related emissions, consumption-based pricing of emissions has been discussed as a way to provide an incentive for non-Annex B countries to reduce their emissions, and hence counteract the off-shoring of emissions and carbon leakage: "the key to reducing carbon leakage may be to use consumption-based GHG inventories, and not production-based inventories" (ref. 7). In practical terms, this approach would be implemented by combining the production-based pricing of domestic emissions with the use of a border tax adjustment (BTA), which taxes imports from (and rebates the carbon price for exports to) countries without emissions regulation based on their embodied emissions (see, e.g., refs 6, 19,20).

Yet, there is no a priori reason to expect that pricing emissions embodied in consumption would result in less carbon leakage than production-based emission pricing. While the latter clearly creates an incentive to shift the *production* of carbon-intensive goods to countries without emission policy, the former will encourage the *consumption* of carbon-intensive goods in such countries (while under full global cap-and-trade they would be indistinguishable[21]): in order to avoid costly abatement in response to a consumption-based emission policy, firms will try to export their emission-intensive products to unregulated markets, resulting in what could be termed 'consumption-leakage' (cf. ref. 22 for an analogous argument on policies aiming at the supply or demand of fossil fuels).

However, without a global carbon price full BTA means that a country puts a (positive) tariff on imported foreign goods whenever their relative carbon content (i.e. the embodied emissions per dollar) is higher than the one of its own export goods. In a world where the 'productivity of carbon' is not uniform across countries, such a tariff only leads to a reduction of carbon leakage if the country against which it is applied is specialized in the production of relatively carbon-intensive goods[23]. In the opposite case it will act as a counterproductive incentive to push the economy from relatively low-carbon export goods to relatively carbon-intensive goods for domestic consumption. As we have shown before, observing a higher relative carbon content for exports than for imports (or vice versa) does not yield robust information on a country's specialization. As a consequence, switching from production to consumption-based pricing of emissions could potentially increase carbon leakage.

Link to trade theory

At first glance, the intuition behind factor content trade and net transfers of emissions is straightforward: if one knows that producing a good consumes a certain amount of fossil fuels, then the respective good can be associated with the corresponding carbon emissions. If this good is exported and used elsewhere, these 'embodied' emissions can be attributed to the final user.

Also the next step of viewing net emission transfers as an indicator of specialization is not *per se* far-fetched: indeed, in a world in which trade in goods and factors are perfect substitutes, a country that is a net exporter of a certain production factor, e.g. emissions, will also have a comparative advantage in the production of goods that use this factor intensively. This view of global trade – which inspired Leontief's original analysis – goes back to Vanek's[24] formulation of the Heckscher-Ohlin model, known as the HOV model. It is based on the central assumption of the Heckscher-Ohlin theory of international trade, namely that trade between countries is driven by differences in factor endowments[25], whereas tastes and production technologies are assumed as identical in all countries. The model implies that trade in goods can be regarded as a substitute for trade in factors and that in the resulting 'integrated equilibrium', traded goods can be interpreted as representing the factors employed in their production[26,27]. However, the model has repeatedly been shown to yield a poor description of trade patterns observed in reality[28-31], echoing Markusen's[32] warning that "the widely held notion that trade in goods and factors are substitutes is in fact a rather special result".

The most compelling reason to empirically reject the HOV model is that different countries use their factor endowments with different levels of productivity[33,34], which can most plausibly be explained by differences in technologies or institutional quality[35,36]. With different factor productivities, one country can produce a good using less of any production factor than its trading partners, which violates one of the HOV model's central assumptions[37,38] and leads, for instance, to the paradoxical result that poor countries appear to be net exporters of *all* factors of production[39]. Yet, this finding is not particularly surprising if one takes into account these countries' lower factor productivities, due to which they tend to employ more of each production factor to produce one dollar of output. Consequently, outside the restrictive assumptions of the HOV model comparing production factors embodied in one country's exports with those of its imports amounts to comparing two quantities that do not share a common basis[40]. Importing a good that has been produced using a certain combination of production factors cannot be regarded as equivalent to importing the embodied production factors, as, using the same amount of these factors, the importing country would generally produce a different quantity of the respective good.

Outlook

Drawing on insights from trade theory and its 'factor content of trade' concept, the present note has argued that it is not possible to directly use the observed net transfers (imports or exports) of embodied emissions to guide the design of climate policies. For instance, the considerable net emission transfer from China to the US does not necessarily imply that trade restrictions imposed by the latter would reduce the former's emissions. The main reason is that the observed net transfers can in principle result from many factors including trade imbalances and differences in the fuel mix used, efficiency achieved, and types of products produced in different countries. In fact, in case of the net import of emissions by the US from China, our decomposition suggests that about 45% of the total transfer can be attributed to the large trade deficit the US runs with China. Consequently, a hypothetical policy of the US that would apply a tariff on imports from China in proportion to their carbon content can be expected to have an impact on China's current specialization on the export of carbon-intensive goods (which we found to account for roughly 20% of the net emission transfer), but it is far from clear how it would affect, among other, the trade deficit or the energy- and carbon-intensity of the Chinese economy. On the other side, an increased effort of the US to decarbonize its own economy would lead to a counterintuitive worsening of its 'carbon trade deficit', while an increase in its carbon-intensity would have an ameliorating effect, but be in obvious contradiction to the objectives of climate policy.

By calculating the amount of emissions embodied in international trade, previous research has provided valuable information that constitutes a necessary–albeit not sufficient–basis to guide policy design. By means of a decomposition analysis we have indicated one way in which the currently available data can be used to study specialization and other possible determinants of international emissions transfers. However, this analysis has remained very exemplary and should be extended by including more countries. Moreover–as is always the case for this type of analysis–a decomposition of emission transfers is not unique and the approach proposed by us not necessarily the most fruitful. Finally, several recent contributions have proposed modifications to the concept of the factor content of trade[41-44], which could provide valuable insights for the further analysis of carbon embedded in international trade.

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Author Contributions

Both authors contributed equally to the formulation and writing of this manuscript.

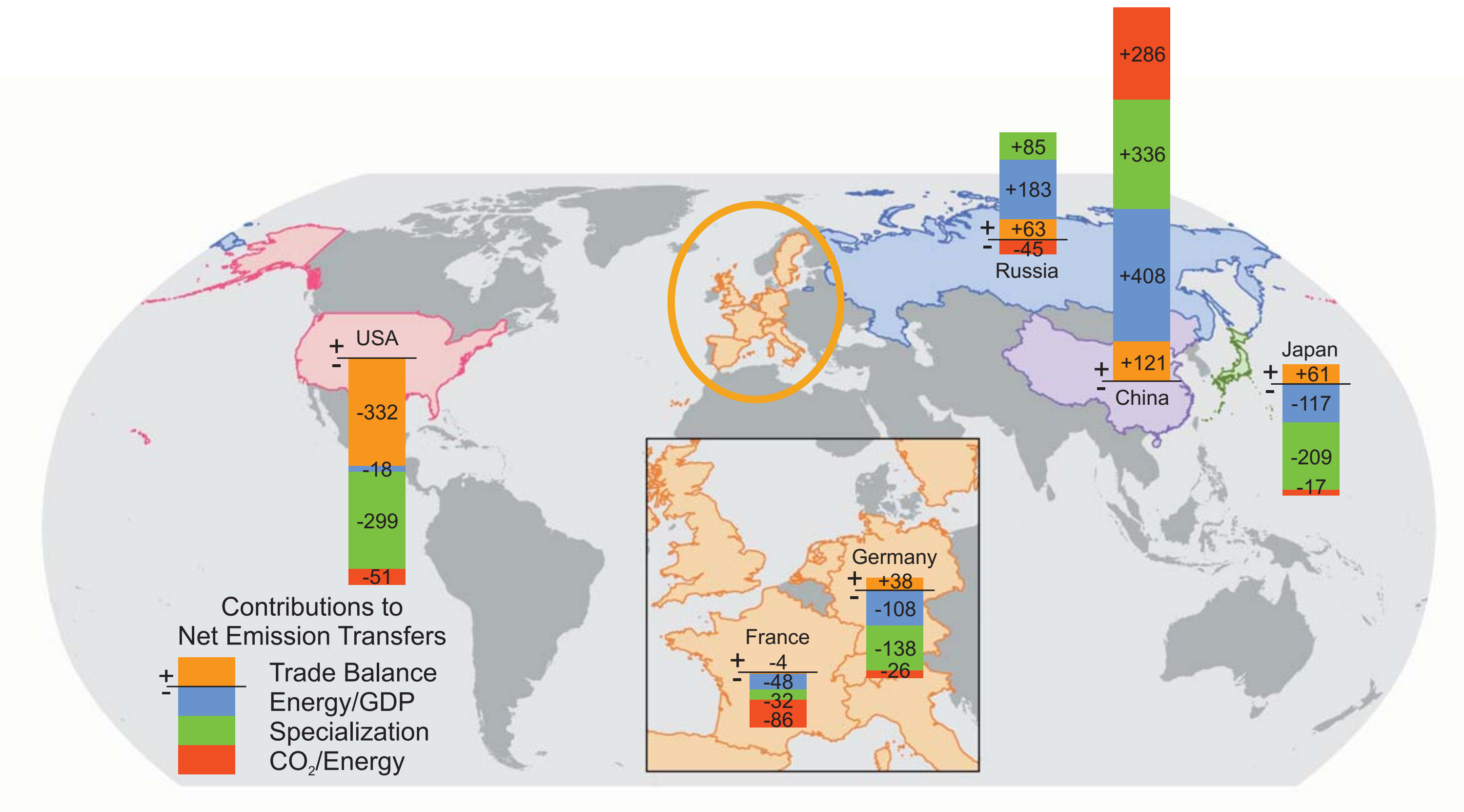
Competing Financial Interests

The authors declare no competing financial interests.

Figure Legends

Figure 1: ***Decomposition of net exports of embodied emissions (in MtCO$_2$) for selected countries***. *'CO_2/Energy' and 'Energy/GDP' refer to the amount of net exported emissions that can be attributed to the country's particular economy-wide energy and carbon intensity (as compared to world average), respectively. 'Specialization' is measured by comparing the carbon-intensity [CO_2/$] of exports with that of total production. Data for 2004, as reported in Davis and Caldeira (2010). GDP measured at purchasing power parity (PPP).*

Figure 2: ***Decomposition of selected net transfers of embodied emissions (in MtCO$_2$) resulting from bilateral trade***. *'Difference in CO_2/Energy' and 'Difference in Energy/GDP' refers to the amount of transferred emissions that can be attributed to countries' differing economy-wide energy and carbon intensities, respectively. 'Specialization' is measured by comparing the carbon-intensity [CO_2/$] of exports with that of total production. Data for 2004, as reported in Davis and Caldeira (2010). 'WEU' comprises nine western European countries: France, Germany, Italy, Luxembourg, Netherlands, Spain, Sweden, Switzerland, United Kingdom. GDP measured at purchasing power parity (PPP).*



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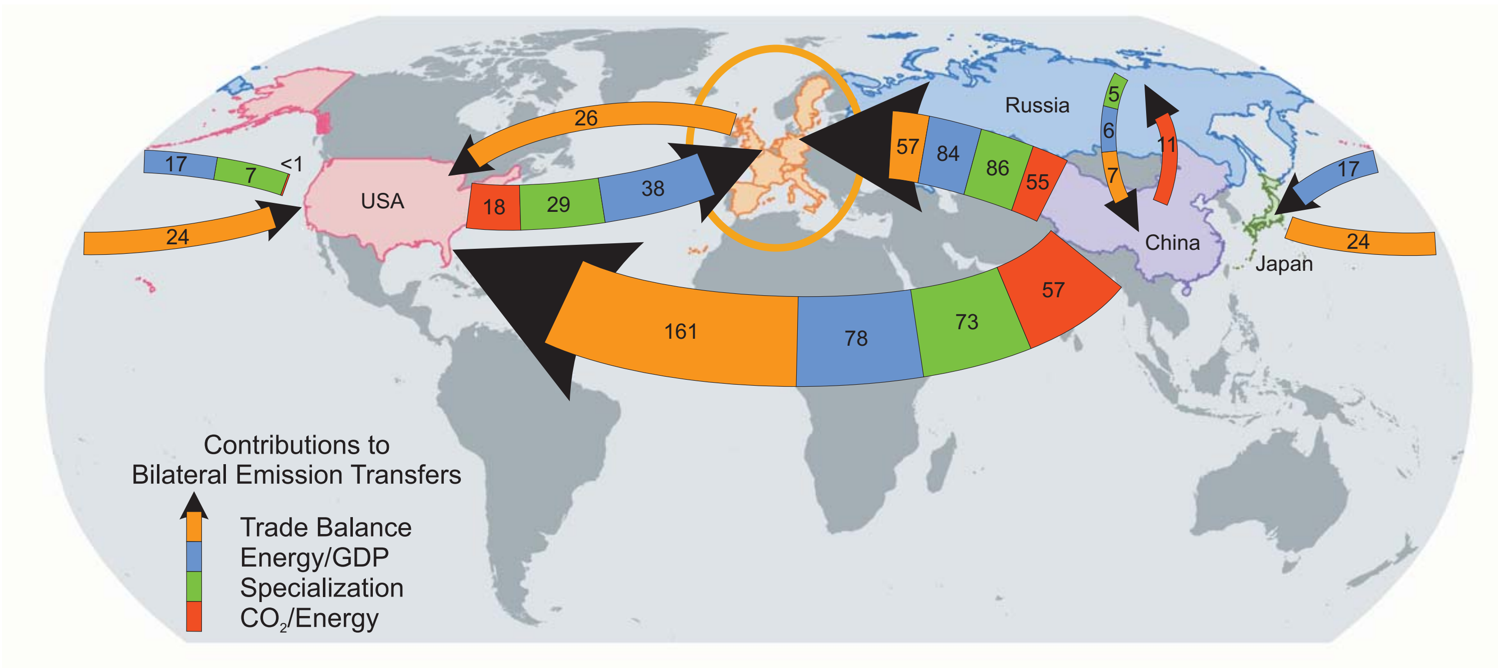
Contributions to
Net Emission Transfers
Trade Balance
Energy/GDP
Specialization
CO_2/Energy



Russia
USA
China
Japan
26
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84
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161
78
73
57
Contributions to
Bilateral Emission Transfers
Trade Balance
Energy/GDP
Specialization
CO2/Energy