Which countries have offshored carbon dioxide emissions in net terms?

Darwili, Aldy; Schröder, Enno

DOI
10.1016/j.ecolecon.2025.108597

Publication date
2025

Document Version
Final published version

Published in
Ecological Economics

Citation (APA)
Darwili, A., & Schröder, E. (2025). Which countries have offshored carbon dioxide emissions in net terms? *Ecological Economics*, *235*, Article 108597. https://doi.org/10.1016/j.ecolecon.2025.108597

Ecological Economics 235 (2025) 108597

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Methodological and Ideological Options

Which countries have offshored carbon dioxide emissions in net terms?

Aldy Darwili, Enno Schröder *

Delft University of Technology, Faculty of Technology, Policy, and Management, Jaffalaan 5, 2628BX Delft, Netherlands

ARTICLE INFO

Keywords:
Carbon dioxide
Carbon accounting
Climate change
Embodied emissions
Global value chains
Input–output
Offshoring
Outsourcing

ABSTRACT

We estimate the extent of emission offshoring at the country level in net terms. We define net emission onshoring as the difference between the emissions domestic producers generate by exporting and the emissions they avoid by importing. Using the multi-regional input–output (MRIO) model and the OECD Inter-Country Input-Output (ICIO) Table, we report levels and trends in net emission onshoring for 45 countries between 1995–2018. Service-oriented economies with trade deficits (USA, UK, India) are net offshoring emissions. China is net onshoring emissions. The scale of net onshoring is small relative to production-based emissions. National emissions and GDP have decoupled in many developed countries, even when accounting for trade. In a cross-section of countries, there is no robust association between net onshoring and per-capita income.

1. Introduction

International trade implies the geographic separation of consumption and production. Production-based emission accounting attributes the carbon dioxide released during the production phase to the producing country, regardless of where the products are finally consumed. The emissions generated by production are said to be "embodied" in the traded products. When, e.g., Germany's car manufacturers produce cars ultimately purchased by foreign consumers, the car production increases Germany's production-based emissions. If, hypothetically, the foreign demand for cars was satisfied by foreign production, Germany's production-based emission would be lower. At the same time, Germany's consumers satisfy their demand partly by importing products from abroad. The imports effectively avoid emissions in Germany: Germany's producers would emit more carbon dioxide if they produced the imported products. How do the emissions embodied in exports compare to the emissions avoided by imports?

We estimate net emission onshoring at the country level as the difference between the emissions embodied in exports and the emissions avoided by imports. The literature refers to this difference as the balance of avoided emissions (Ackerman et al., 2007; Peters et al., 2007; Arto et al., 2014; Zhang et al., 2017; Wu et al., 2022). The balance of avoided emissions equals the difference between the emissions embodied in *gross* exports and the emissions avoided by *gross* imports. The emissions embodied in gross trade flows are estimated on the basis of the Emissions Embodied in Bilateral Trade (EEBT) approach. The EEBT approach facilitates single-country studies with low data requirements: only national input–output tables and national emission factors are required.

With the construction of global Multi-Regional Input-Output (MRIO) tables, it became possible to estimate the emissions embodied in final demand Peters and Hertwich (2008), Peters (2008a), Hertwich and Peters (2009), Davis and Caldeira (2010). Emissions embodied in final demand are estimated on the basis of the MRIO approach. The term *emissions embodied in exports* has come to refer to the domestic emissions embodied in foreign final demand, and the term *emissions embodied in imports* has come to refer to the foreign emissions embodied in domestic final demand. The trends and cross-country patterns in these variables are well-known (e.g., Peters et al., 2011). The "rich" OECD countries tend to record negative emission transfers (the emissions embodied in imports exceed the emissions embodied in exports) while the "poor" non-OECD countries tend to record positive emission transfers (the emissions embodied in exports exceed the emissions embodied in imports). The net emission transfers between the OECD aggregate and the non-OECD aggregate peaked in 2006 and decreased slightly since then (Wood et al., 2019).

The literature uses the MRIO approach to estimate emission transfers; we use it to estimate net emission onshoring. When domestic producers produce for foreign final demand, we regard this as emission onshoring and estimate it by the emissions embodied in exports. When domestic producers avoid emissions because domestic consumers satisfy their final demand through foreign production, we regard this as emission offshoring. To estimate emission offshoring (the domestic emissions avoided), the domestic production technologies and domestic emission intensities are relevant. The so-called *domestic technology assumption* is clear cut in the EEBT model (e.g., Arto et al., 2014), but it has no obvious analog in the MRIO model. We propose a variant

* Corresponding author.
E-mail address: e.schroeder@tudelft.nl (E. Schröder).

https://doi.org/10.1016/j.ecolecon.2025.108597
Received 31 May 2024; Received in revised form 9 January 2025; Accepted 6 March 2025
Available online 17 April 2025

of the domestic technology assumption for the MRIO model. We apply domestic technological coefficients and domestic emission intensities to the rest of the world's value chains.

By studying net onshoring, we can determine which countries "benefit" from international trade in embodied emissions. Net onshoring is the relevant variable to assess the claim that international trade implicitly lowers the rich countries' emissions while raising the developing countries' emissions. Production-based accounting is the policy-relevant accounting principle. We document which countries record higher policy-relevant emissions due to international trade and which ones record lower emissions. The analysis reveals that the USA, the UK, and India – service-oriented economies with trade deficits – are net offshoring emissions. China is net onshoring emissions, but on a modest scale relative to national production-based emissions (Section 4.1). Net onshoring does not account for the decoupling of national emissions and economic growth observed in many OECD countries in the 21st century. In a cross-section of countries, there is no robust association between net onshoring and per-capita income (Section 4.2).

Net emission transfers and net emission onshoring are different concepts; we are not the first ones to emphasize the distinction, but the concepts are still sometimes confused.[1] Concerns about the increase in developing country emissions supported by demand in rich countries ("weak carbon leakage") originally motivated studies of the emissions embodied in trade (Peters, 2008b). But developing countries also avoid emissions through imports. The literature spawned by Peters focused on net emission transfers, which is the "wrong" emission balance if we are concerned with the impacts of trade on a region's emissions in net terms. The relevant emission balance in this context is the difference between emissions embodied in exports and the emissions avoided by imports (net emission onshoring).

To show which countries benefit from trade (in terms of emissions) is valuable in its own right. In addition, our analysis relates to similar studies which estimate the balance of avoided emissions based on the EEBT approach (López et al., 2013; Zhang et al., 2017; López et al., 2018). The primary goal of these studies is to test the Pollution Haven Hypothesis and to investigate whether trade is environmentally efficient, i.e., whether a country's observed trade flows increase or decrease global emissions relative to a hypothetical scenario without trade. The studies in general find that trade decreases global emissions, which contradicts the Pollution Haven Hypothesis. If the Pollution Haven Hypothesis were to hold, countries with relatively clean production technologies would import emission-intensive products and countries with relatively dirty production technologies would export them (see Section 4.2). Our net onshoring measure based on the MRIO approach is not designed to test the Pollution Haven Hypothesis; although we make slightly different methodological choices, our findings corroborate the antecedent studies in that we find that trade is environmentally efficient.

2. Methods

Our goal is to estimate net emission onshoring, understood as the emissions embodied in exports minus the emissions avoided by imports. The emissions avoided by imports are conventionally calculated on the basis of the EEBT approach. Here we propose a calculation on the basis of the MRIO approach.

As a preliminary step, we introduce the notation for input–output model and the formulas for the emissions embodied in trade. The environmentally-extended MRIO model (Leontief, 1970; Miller and Blair, 2009) can be written in general form for n sectors and m countries, but for ease of exposition we present the two-country model written compactly as:

$$\begin{bmatrix} e^{11} & e^{12} \\ e^{21} & e^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^1 & 0 \\ 0 & \hat{q}^2 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} \\ L^{21} & L^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix} \tag{1}$$

On the left-hand side is the global emissions matrix E. The first object on the right-hand side contains the diagonalized global direct emission intensity vector q (the hat denotes diagonalization). The second object on the right-hand side is the global Leontief inverse matrix L, and the third object is the global final demand matrix Y. The objects are composed of sub-matrices and sub-vectors for the countries 1 and 2 (the focus country and the rest of the world). Country 1's emissions embodied in exports are given by:

$$EEX^1 = e^{12} = \hat{q}^1 L^{11} y^{12} + \hat{q}^1 L^{12} y^{22} \tag{2}$$

Net emission transfers equal the balance of emissions embodied in trade: $BEET^1 = EEX^1 - EEM^1$, where EEM^1 represent the emissions embodied in imports ($e^{21} = \hat{q}^2 L^{21} y^{11} + \hat{q}^2 L^{22} y^{21}$). When the BEET is positive ($EEX^1 > EEM^1$), the focus country net transfers emissions to the ROW.

We are interested in the emissions avoided by imports, meaning the emissions that focus country producers would generate if they produced the foreign products consumed by focus country end-users. We postulate that imports are produced on the basis of the focus country's emission intensities and production recipes. The meaning of "production recipe" is slightly different in the EEBT model and the MRIO model. In the EEBT model, a sector's production recipe is given by n technical coefficients, which reflect inputs from producing sectors in the focus country. In the MRIO model, a sector's production recipe is given by $n \cdot m$ technical coefficients, which reflect inputs from producing sectors in the focus country and the ROW. As an example, consider Germany's automotive sector using intermediate inputs from German and foreign producers. Given our MRIO approach, we regard all sectors supplying inputs to Germany's automotive sector as part of Germany's automotive value chain. The production recipe of Germany's automotive sector includes inputs from producers located abroad.

To estimate the emissions avoided by imports, we adjust the MRIO model:

$$\begin{bmatrix} \dot{e}^{11} & \dot{e}^{12} \\ \dot{e}^{21} & \dot{e}^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^1 & 0 \\ 0 & \hat{q}^1 \end{bmatrix} \begin{bmatrix} \dot{L}^{11} & \dot{L}^{12} \\ \dot{L}^{21} & \dot{L}^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix} \tag{3}$$

The equation system (3) reflects the focus country's production recipes. The focus country's (country 1's) emission intensities, $\hat{q}^1$, have replaced the ROW's (country 2's) emission intensities, $\hat{q}^2$. The adjusted Leontief inverse, $\dot{L}$, has replaced the Leontief inverse, L. The adjustment to the Leontief inverse is explained further below. The formula for country 1's emissions avoided by imports is:

$$EAM^1 = \dot{e}^{21} = \hat{q}^1 \dot{L}^{21} y^{11} + \hat{q}^1 \dot{L}^{22} y^{21} \tag{4}$$

It is analogous to the formula for the emissions embodied in imports, but it uses $\hat{q}^1$ and $\dot{L}$ in place of $\hat{q}^2$ and L.

Net emission onshoring is defined as:

$$NetOn^1 = EEX^1 - EAM^1 \tag{5}$$

Net onshoring compares the focus country's observed emissions generated by domestic production for foreign final demand ("emission onshoring") and the focus country's hypothetical emissions that would have been generated had the focus country satisfied its final demand for foreign products through the technology of its own value chains ("emission offshoring"). When $NetOn > 0$, the focus country is net onshoring emissions. $NetOn > 0$ can be interpreted in two ways representing two sides of the same coin: (i) observed trade flows increase the focus country's emissions, and (ii) the focus country would generate less emissions in a hypothetical no-trade scenario. When $NetOn < 0$, the focus country is net offshoring emissions, meaning observed trade

[1] Liu (2015) guards against the careless use of terms like "emission transfers", "leakage", and "outsourcing".

decreases the country's emissions and hypothetical no-trade would increase its emissions.

The net onshoring variable measures the "impact" of trade.[2] The impact of trade on emissions, thus defined, includes the impact of aggregate trade imbalances. The implicit assumption is that trade-deficit countries would increase aggregate production to match domestic demand while trade-surplus countries would decrease aggregate production to match domestic demand. Summing net onshoring over all countries will give the impact of global trade on global emissions.

In a related literature thread, the analog to the net onshoring variable based on the MRIO approach is the balance of avoided emissions based on the EEBT approach (López et al., 2013; Zhang et al., 2017; López et al., 2018). These studies primarily investigate the Pollution Haven Hypothesis (see Section 4.2); to pursue their research objective, the authors eliminate the influence of the aggregate trade balance on the balance of avoided emissions. Our primary research objective is to show which countries are offshoring emissions in net terms. We consider running a trade deficit as one way of offshoring emissions, hence we do not adjust the variable for aggregate trade deficits/surpluses.

2.1. Details on the adjusted Leontief inverse

The adjusted Leontief inverse is based on a decomposition first introduced by Xu and Dietzenbacher (2014) and explained in the original paper and in this section.

We decompose a sector's production recipe into the product of n *technological coefficients*, which represent the intermediate input requirements regardless of geographical origin; and m import shares, which represent the shares of a given intermediate input in the total intermediate inputs required.

Let a_{ij}^{sr} be an element of the global technical coefficient matrix A, representing the purchase of intermediate input by sector j in country r from sector i in country s. The sum over all supplying countries s yields the technological coefficient:

$$h_{ij}^{r} = \sum_{s=1}^{m} a_{ij}^{sr} \tag{6}$$

These coefficients are collected in country r's technological coefficient matrix H^r, which has the dimension $n \times n$:

$$H^{r} = \sum_{s=1}^{m} A^{sr} \tag{7}$$

where A^{sr} is a sub-matrix of the global technical coefficient matrix A with the dimension $n \times n$.

The trade structure matrix of the intermediate inputs reflecting the origin (geographical composition) is given by:

$$T = \begin{bmatrix} T^{11} & \cdots & T^{1m} \\ \vdots & \ddots & \vdots \\ T^{m1} & \cdots & T^{mm} \end{bmatrix} \tag{8}$$

Each element in the trade structure matrix represents the share of every input i in country r that is required by sector j in country r:

$$t_{ij}^{sr} = a_{ij}^{sr} / h_{ij}^{r} \tag{9}$$

The sum over all supplying countries s adds up to one.

The global technical coefficient matrix can be written as ($\otimes$ represents the Hadamard product of element-wise multiplication):

$$A = \begin{bmatrix} T^{11} \otimes H^{1} & \cdots & T^{1m} \otimes H^{m} \\ \vdots & \ddots & \vdots \\ T^{m1} \otimes H^{1} & \cdots & T^{mm} \otimes H^{m} \end{bmatrix} \tag{10}$$

To capture the idea that country 1's imports are produced using the technology of country 1's value chains, the foreign technological coefficients are replaced by country 1's technological coefficients, H^1, resulting in the adjusted global technical coefficient matrix $\dot{A}$:

$$\dot{A} = \begin{bmatrix} T^{11} \otimes H^{1} & \cdots & T^{1m} \otimes H^{1} \\ \vdots & \ddots & \vdots \\ T^{m1} \otimes H^{1} & \cdots & T^{mm} \otimes H^{1} \end{bmatrix} \tag{11}$$

The adjusted Leontief inverse follows as $\dot{L} = (I - \dot{A})^{-1}$. It is used in system (3). The emissions avoided by imports are calculated on the basis of system (3) and reflect the focus country's emission intensities and production recipes.

3. Data

We use the 2021 edition of the OECD Inter-Country Input-Output (ICIO) Database (OECD, 2021a). The database provides the monetary industry-by-industry transactions and final demands for 45 sectors and 66 countries (93% of global GDP) and a ROW aggregate between 1995–2018. It includes 38 OECD countries and 28 non-OECD economies.

The vector of the direct emission intensities comes from OECD (2021b). The emission intensity is measured in tonnes per million USD. The emission intensities are based on the IEA's CO2 Emissions from Fossil Fuel Combustion (IEA, 2019) and their construction is described in Yamano and Guilhoto (2020). Direct emissions from household consumption (e.g., fuel combustion in private cars) are given separately. These emissions are part of a country's production-based emissions (PBE) and consumption-based emissions (CBE), but not part of traded emissions.

We complement the IO data with population and gross domestic product (GDP) variables from the Penn World Table Version 10 (PWT10, Feenstra et al. (2015)). We calculate income per capita by dividing the output-side real GDP at chained PPPs in 2017 US$ by population.

The complete data set covers 66 countries between 1995–2018.[3] We exclude small countries from the analysis because the domestic technology assumption is most appropriate for large economies capable of producing most of the products consumed (we return to this issue in Section 4). We set the small-country threshold at a 2018 population of 7.5 million people.[4] The final sample includes 45 countries.

4. Results and discussion

4.1. Net emission on/off-shoring over time

Fig. 1 plots the evolution of net emission onshoring and the conventional emission balance (BEET) in six major economies from 1995–2018. The figure shows two large developed countries with relatively large service sectors (the USA and the UK), two large developed countries with relatively large manufacturing sectors (Japan and Germany), and the two largest developing economies (China and India). The USA and

[2] In an input–output setting, the "impact of trade on emissions" should not be understood as the "causal effect of trade on emissions". The input–output model holds constant the scale and composition of final demand and the production techniques. Given demand and given technology, how would emissions change in a hypothetical no-trade scenario in which domestic producers satisfy domestic demand? Demand and technology, however, are partly determined by trade. The causal effect of trade on emissions will reflect, among other things, the influence of trade on the scale and composition of demand and the production techniques (Antweiler et al., 2001; Copeland and Taylor, 2004; Cherniwchan and Taylor, 2022).

[3] The Online Supporting Material lists all countries and all sectors (Table 7 and Table 8).

[4] In the interest of transparency: we initially set the threshold at 10 million, a nice and round number. We lowered the threshold after noticing it would exclude Sweden and Switzerland. Both countries are worth studying on account of their trade-intensive economies with exceptionally clean energy systems.

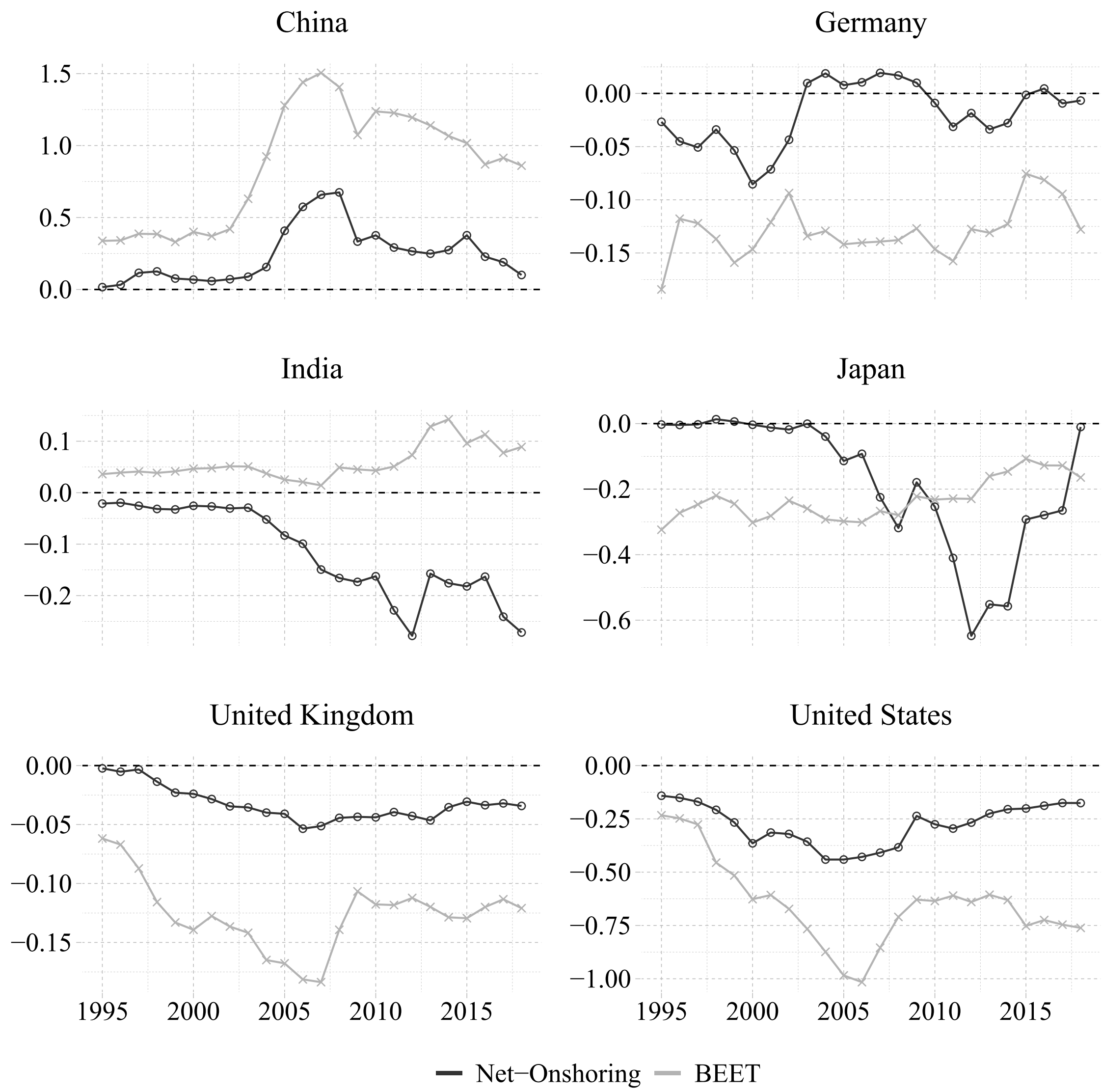

Fig. 1. Net onshoring and the BEET in six major economies 1995–2018, $GtCO_2$
Notes: own calculations. Net onshoring represents the difference between the emissions embodied in exports and the emissions avoided by imports. The BEET represents the difference between the emissions embodied in exports and the emissions embodied in imports.

China are polar opposites: the USA net offshores emissions ($NetOn < 0$), meaning the Americans avoid more emissions by importing than they generate by exporting; while China net onshores emissions ($NetOn > 0$), meaning the Chinese generate more emissions by exporting than they avoid by importing. The BEET has attracted a lot of attention, and indeed the magnitudes are large in both countries. Net onshoring, by contrast, occurs on a smaller scale. At the beginning of the analysis period and towards the end, China neither onshores emissions nor offshores emissions in net terms (net onshoring is essentially zero in 1995 and 2018).

In China and Germany, the big trade-surplus countries, changes in net onshoring roughly track changes in the trade balance: net onshoring increases along with the emergence of the trade surpluses in the early 2000s. Yet, at the end of the analysis period, neither of the two trade-surplus economies is onshoring emissions. Germany would be net onshoring emissions if not for the contribution of the energy mining sector.[5] Germany's tiny energy mining sector operates with a high emission intensity (relative to other sectors in Germany and relative to the same sector in other countries). The high emission intensity combines with a relatively large quantity of imported energy products, so that on balance the sector helps Germany to avoid emissions.

India is an interesting case: the BEET is positive, as is typical in many developing countries, but India is net offshoring emissions throughout the analysis period. The observed trade flows are in effect reducing India's production-based emissions. We expect to see this pattern in an economy exporting services (low emission intensity) and importing manufactured goods and raw materials (high emission intensity). A decomposition analysis to quantify the importance of trade-balance effects and composition effects is beyond the scope of this paper. In general, a trade-deficit country produces less than it consumes; ceteris paribus, it will net offshore emissions. The USA and the UK are service-oriented economies running persistent trade deficits; as expected, they are net offshoring emissions.

As in Germany, energy products also play an important role in Japan's (somewhat peculiar) net onshoring trend. The energy mining sector is small and its emission intensity is extremely high. The share of energy in Japan's total imports was rising, with peaks in 2008 and 2012, when oil prices were high. By 2018, the share of energy products in Japanese imports had returned to the levels recorded at the beginning of the analysis period.

[5] OECD-ICIO sector title and code: "Mining and quarrying, energy producing products" (D05T06).

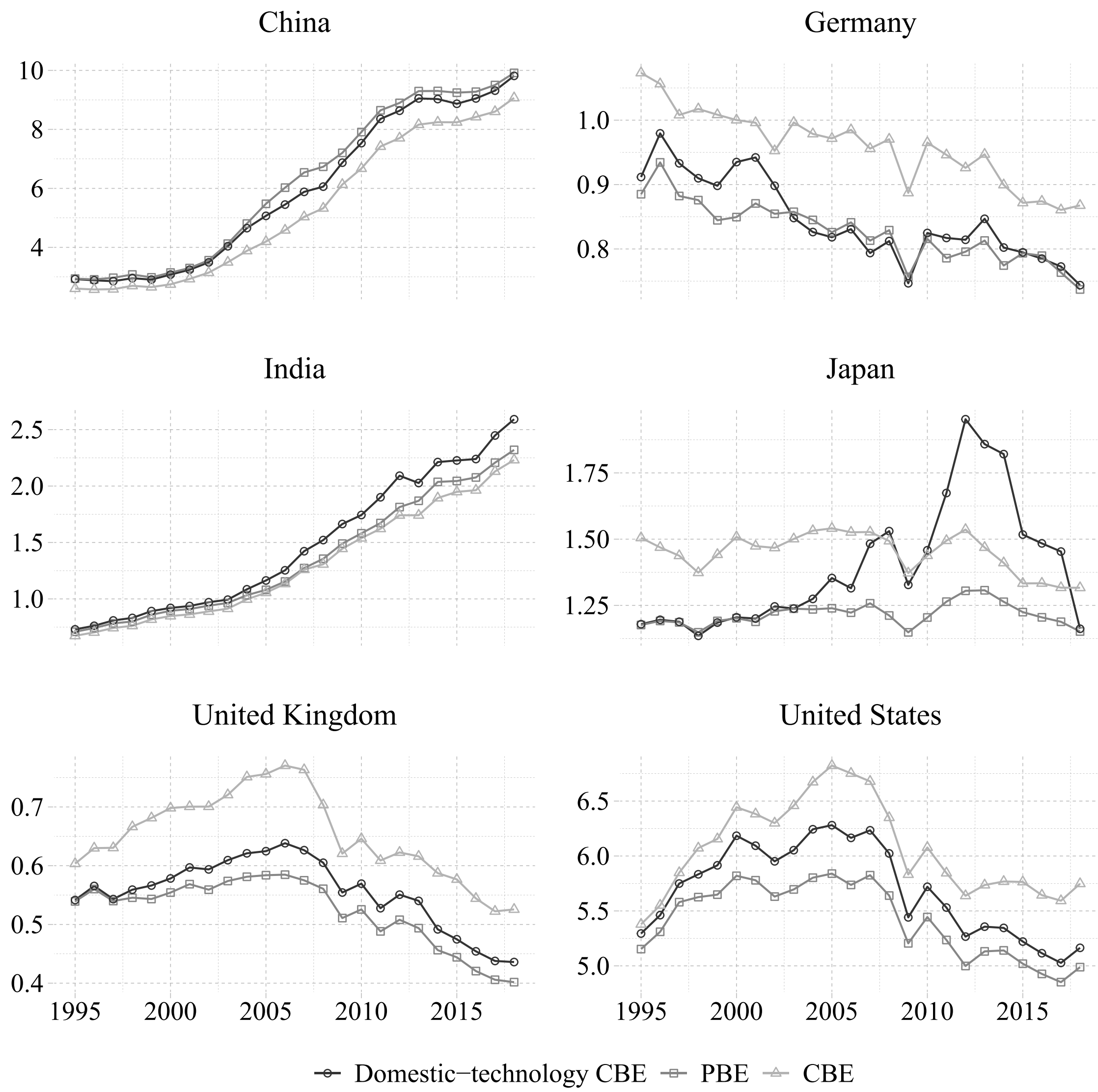

Fig. 2. National emissions, $GtCO_2$.
Notes: own calculations. PBE = production-based emissions. Domestic-technology CBE represent PBE minus the emissions embodied in exports plus the emissions avoided by imports. CBE = consumption-based emissions.

4.1.1. Domestic-technology CBE

Do national emission trends change when we adjust for emission onshoring and offshoring? To explore the question, we adjust the PBE by adding the offshored emissions and subtracting the onshored emissions:

$$\text{Domestic-technology CBE} = \text{PBE} - \text{Net Onshoring} = \text{PBE} - \text{EEX} + \text{EAM} \tag{12}$$

The "domestic-technology CBE" represent the emissions the focus country would record if it did not produce its exports (products consumed by foreign end-users) and instead produced its imports (products consumed by domestic end-users). To be clear, the domestic-technology CBE differ from the regular CBE because the emissions avoided by imports, rather than the emissions embodied in imports, enter the variable.[6]

The domestic-technology CBE and the PBE are both increasing in India and China, are decreasing in Germany, and are first increasing and then decreasing in the USA and the UK (Fig. 2). Overall, the two variables are highly correlated and display the same trends. This is not surprising, because the magnitude of net onshoring is small in relation to the PBE. Accounting for net onshoring does not dramatically change national emission trends.

Japan is an unusual case. The country demonstrates the limits of the domestic technology assumption. Japan is notoriously scarce in natural resources, meaning it cannot, and does not, produce the imported energy products in significant quantities.[7] The energy mining sector is tiny, its input–output coefficients are volatile. The coefficients probably do not reflect the technology that would be employed if Japan mined energy products at much larger scales. To be clear, all applications of the domestic technology assumption face this problem, including all studies estimating the balance of avoided emissions (e.g., Ackerman et al., 2007; Dietzenbacher and Mukhopadhyay, 2007; Arto et al., 2014; Wu et al., 2022). The domestic technology assumption is most appropriate for large, diversified economies producing most of

[6] CBE = PBE − BEET = PBE − EEX + EEM.

[7] In the jargon of input–output analysis, the energy products can be viewed as non-competing imports.

Table 1
Cross-country regressions of net onshoring on income per capita.

	Net Onshoring			BEET		
	(1)	(2)	(3)	(4)	(5)	(6)
	1995	2007	2018	1995	2007	2018
Income	0.491**	0.126	0.102	−0.404	−0.441**	−0.343*
	(0.205)	(0.135)	(0.136)	(0.262)	(0.209)	(0.162)
Constant	−14.062***	−7.492	−9.247*	2.148	4.345	5.662
	(4.292)	(4.066)	(4.839)	(5.463)	(6.291)	(5.784)
N	45	45	45	45	45	45
R squared	0.117	0.020	0.013	0.053	0.093	0.094

Notes: own calculations. Simple OLS regressions of net onshoring (and the BEET) expressed in percent of national emissions (the mean of PBE and CBE) on per-capita income in thousand PPP-adjusted US$. The standard errors in parentheses are heteroskedasticity-robust (Huber-White).

* Indicates $p < 0.1$.

** Indicates $p < 0.05$.

*** Indicates $p < 0.01$.

the products consumed. Japan's economy is large and diversified in comparison with many other economies; still, the energy mining sector appears to be a crucial determinant of net onshoring.

4.2. Net emission on/off-shoring across countries

In Fig. 2, the four industrialized countries record higher CBE than PBE, in every year, and the two developing countries record lower CBE than PBE, in every year. There is a well-known negative association between per-capita income and the BEET. In rich countries the BEET tends to be lower than in poor countries, and frequently negative (Davis and Caldeira, 2010; Peters et al., 2011). The right column of Fig. 3 plots the cross-country relationship in the years 1995, 2007, and 2018. Recall that the BEET compares the emissions embodied in exports and the emissions embodied in imports. The variable is largely driven by international technology differences: countries with relatively clean energy sectors and low intermediate inputs requirements tend to record negative BEETs (Jakob and Marschinski, 2013; Kander et al., 2015). The cross-country pattern is easily explained: in general, producers in advanced economies are more efficient and energy systems become cleaner over the course of development. As countries climb up the "energy ladder", the energy mix tends to become less carbon-intensive: coal is replaced first by oil and then by gas, nuclear power, wind, and solar (Burke, 2013).[8]

For the same years, the left column of Fig. 3 plots the relationship between per-capita income and net onshoring. There is a positive association between the two variables, but it is a weak relationship. Table 1 reports the cross-country regressions corresponding to the lines in Fig. 3.[9] The cross-country variation in net onshoring can hardly be explained by income (the R-squared is low), and only in 1995 is the correlation statistically significant ($\alpha = 0.05$). The largest slope coefficient (in column 1) is still small: 0.49 means that one thousand dollars higher per-capita income is associated with half a percentage point higher net onshoring.

Theoretically grounded and empirically robust theories that could explain the cross-country pattern are hard to come by. The Pollution Haven Hypothesis (PHH) implies that countries with strict environmental regulations import emission-intensive ("dirty") products and countries with lax environmental regulations export them (Copeland and Taylor, 1994; Taylor, 2005). Environmental regulations tend to be strict and tightly enforced in rich countries and lax and loosely enforced in poor countries. Therefore, according to the hypothesis, rich countries will import dirty products and poor countries will export them, meaning rich countries will net offshore emissions (assuming balanced trade). The PHH cannot explain the cross-country net onshoring pattern – if anything, rich countries are net onshoring emissions (Fig. 3 and Table 1).[10]

The scatter plots and cross-country regressions should not be misunderstood as exercises designed to test the PHH, or more generally to test the Heckscher–Ohlin factor-endowment theory of comparative advantage and international trade. The net onshoring variable reflects monetary aggregate trade imbalances while the pure theory of trade, which the PHH is part of, abstracts from aggregate trade imbalances.[11] The point is that well-known theories of international trade do not seem to explain the observed cross-country net offshoring pattern.

Net offshoring ($NetOn < 0$) means that the focus country's emissions would be higher in a hypothetical scenario without trade. If a net-offshoring country did not produce for foreign final demand and if it satisfied domestic final demand through domestic production, its emissions would be higher. The USA, the UK, and India are merely the prime examples; most countries in our sample net offshore emissions (only 16 out of 45 countries net onshore emissions in 2018; see Fig. 3). Net offshoring is the norm, which means that production tends to take place where it is environmentally efficient. Whether global emissions would be lower in a no-trade scenario depends on the countries excluded from our sample. Fig. 3 alone cannot be viewed as conclusive evidence, but it echoes related studies which find that observed trade flows serve to reduce global emissions (Chen and Chen, 2011; López et al., 2013; Zhang et al., 2017; López et al., 2018).

4.3. Comparison of MRIO and EEBT approach

In the Online Supporting Material, we compare two methods for the estimation of the emissions avoided by imports (Figure 4). Other

[8] At very low income levels, fossil fuels replace traditional energy and economic growth may increase the energy system's carbon intensity. Our sample does not include low-income countries.

[9] We estimate the models $NetOn_i = \beta_0 + \beta_1 Income_i + u_i$ and $BEET_i = \beta_0 + \beta_1 Income_i + u_i$ by OLS using cross-sectional data from the year 1995, 2007, or 2018. $Income$ refers to PPP-adjusted GDP per capita in thousand international dollars. Net onshoring and the BEET are expressed in percent of national emissions, which are calculated as the simple mean of PBE and CBE. The reported standard errors are robust with respect to heteroskedasticity.

[10] The PHH can be viewed as an application of the Heckscher–Ohlin theory of comparative advantage, which holds that a country specializes in the products that intensively use the abundant production factor. Lax environmental regulations are tantamount to an abundance of natural capital (the use of which generates emissions) and thus imply specialization in dirty products. However, dirty products tend to be capital-intensive. As rich countries are abundant in produced capital, a theory of specialization based on factor endowments can also generate the prediction that rich countries will export dirty products (Antweiler et al., 2001).

[11] Baldwin (2008) reviews the standard Heckscher–Ohlin theory in light of the econometric evidence and describes the successive modifications to the original model. The econometric evidence, on the whole, does not support the PHH (Taylor, 2005; Copeland et al., 2022).

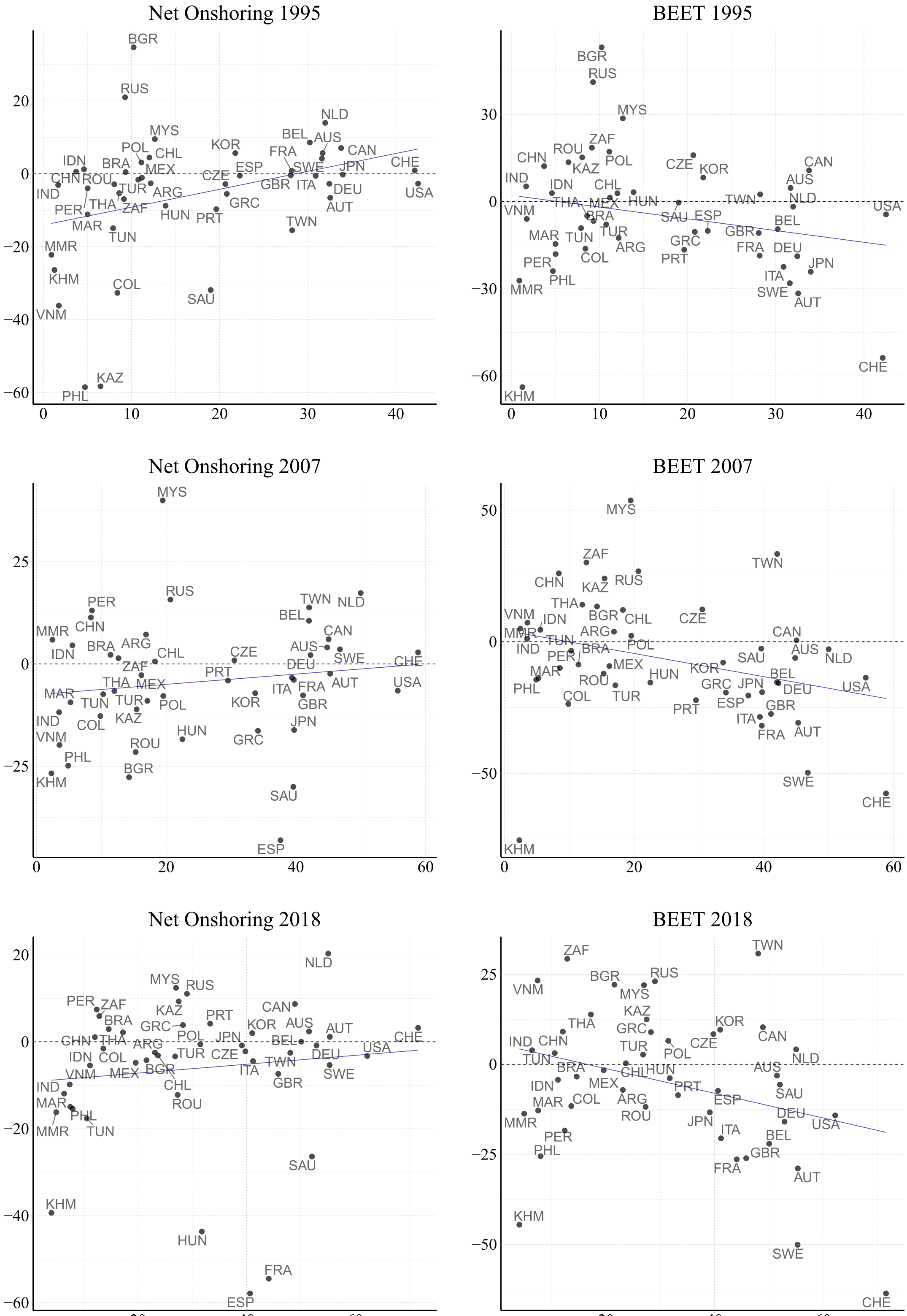

Fig. 3. Net onshoring (and the BEET) vs. income per capita.
Notes: own calculations. Net onshoring and the BEET are both expressed in percent of national emissions (the mean of PBE and CBE). Income per capita is expressed in thousand PPP-adjusted US$.

studies use the EEBT approach to calculate the emissions avoided by gross imports (EAM-EEBT) while this study uses the MRIO approach to calculate the emissions avoided by imports (EAM-MRIO: the domestic emissions avoided by domestic final demand for foreign products). In most cases, the differences between the two methods are small in the following sense: the values of EAM-MRIO and EAM-EEBT are fairly similar compared to the values of the EEM. The domestic technology assumption makes a difference, but the choice of the MRIO model vs. the EEBT model is of secondary importance.

5. Summary and concluding remarks

We focus on net onshoring and apply the domestic technology assumption to estimate the variable. Once international technology differences are eliminated, only the composition of economic activity and the overall trade balance determine net onshoring. We find that service-oriented economies running trade deficits, e.g., the USA, UK, and India, net offshore emissions. These countries record lower emissions than they would if they ceased to produce for foreign final demand and instead satisfied their final demand through domestic production. They benefit from trade in the sense that the observed trade flows reduce the policy-relevant production-based emissions.

In a cross-section of countries, there is no robust association between net onshoring and per-capita income. Some OECD countries net offshore emissions (e.g., the USA) while other OECD countries net onshore emissions (e.g., the Netherlands); some developing countries net offshore emissions (e.g., India) while other developing countries net onshore emissions (e.g., China).

The scale of emission on- and off-shoring is relatively small in net terms. Hence, accounting for net onshoring does not dramatically change national emission trends. Consumption-based emissions, when estimated using the domestic technology assumption ("domestic-technology CBE"), behave similarly as production-based emissions. National emissions, both PBE and CBE, have peaked in many OECD countries, while they are rising in the developing countries (Quéré et al., 2019; Jackson et al., 2019).

CRediT authorship contribution statement

Aldy Darwili: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis. **Enno Schröder:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecolecon.2025.108597.

Data availability

Data will be made available on request.

References

Ackerman, F., Ishikawa, M., Suga, M., 2007. The carbon content of Japan–US trade. Energy Policy 35 (9), 4455–4462.

Antweiler, W., Copeland, B.R., Taylor, M.S., 2001. Is free trade good for the environment? Am. Econ. Rev. 91 (4), 877–908.

Arto, I., Roca, J., Serrano, M., 2014. Measuring emissions avoided by international trade: Accounting for price differences. Ecol. Econom. 97, 93–100.

Baldwin, R.E., 2008. The Development and Testing of Heckscher-Ohlin Trade Models: A Review. MIT Press.

Burke, P.J., 2013. The national-level energy ladder and its carbon implications. Environ. Dev. Econ. 18 (4), 484–503.

Chen, Z.M., Chen, G.Q., 2011. Embodied carbon dioxide emission at supra-national scale: A coalition analysis for G7, BRIC, and the rest of the world. Energy Policy 39 (5), 2899–2909.

Cherniwchan, J., Taylor, M.S., 2022. International trade and the environment: Three remaining empirical challenges. In: Oxford Research Encyclopedia of Economics and Finance.

Copeland, B.R., Shapiro, J.S., Scott Taylor, M., 2022. Chapter 2 - Globalization and the environment. In: Gopinath, G., Helpman, E., Rogoff, K. (Eds.), Handbook of International Economics. In: Handbook of International Economics: International Trade, Volume 5, vol. 5, Elsevier, pp. 61–146.

Copeland, B.R., Taylor, M.S., 1994. North-south trade and the environment. Q. J. Econ. 109 (3), 755–787.

Copeland, B.R., Taylor, M.S., 2004. Trade, growth, and the environment. J. Econ. Lit. 42 (1), 7–71.

Davis, S.J., Caldeira, K., 2010. Consumption-based accounting of CO2 emissions. Proc. Natl. Acad. Sci. 107 (12), 5687–5692.

Dietzenbacher, E., Mukhopadhyay, K., 2007. An empirical examination of the pollution haven hypothesis for India: Towards a green leontief paradox? Environ. Resour. Econ. 36 (4), 427–449.

Feenstra, R.C., Inklaar, R., Timmer, M.P., 2015. The next generation of the penn world table. Am. Econ. Rev. 105 (10), 3150–3182.

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: A global, trade-linked analysis. Environ. Sci. Technol. 43 (16), 6414–6420.

IEA, 2019. CO2 Emissions from Fuel Combustion 2019. International Energy Agency, Paris, http://dx.doi.org/10.1787/2a701673-en.

Jackson, R.B., Friedlingstein, P., Andrew, R.M., Canadell, J.G., Quéré, C.L., Peters, G.P., 2019. Persistent fossil fuel growth threatens the Paris agreement and planetary health. Environ. Res. Lett. 14 (12), 121001.

Jakob, M., Marschinski, R., 2013. Interpreting trade-related CO2 emission transfers. Nat. Clim. Chang. 3 (1), 19–23.

Kander, A., Jiborn, M., Moran, D.D., Wiedmann, T.O., 2015. National greenhouse-gas accounting for effective climate policy on international trade. Nat. Clim. Chang. 5 (5), 431–435.

Leontief, W., 1970. Environmental repercussions and the economic structure: An input-output approach. Rev. Econ. Stat. 52 (3), 262–271.

Liu, L., 2015. A critical examination of the consumption-based accounting approach: has the blaming of consumers gone too far? WIREs Clim. Chang. 6 (1), 1–8, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/wcc.325.

López, L.A., Arce, G., Kronenberg, T., Rodrigues, J.F.D., 2018. Trade from resource-rich countries avoids the existence of a global pollution haven hypothesis. J. Clean. Prod. 175, 599–611.

López, L.A., Arce, G., Zafrilla, J.E., 2013. Parcelling virtual carbon in the pollution haven hypothesis. Energy Econ. 39, 177–186.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions. Cambridge University Press.

OECD, 2021a. OECD Inter-Country Input-Output Database, 2021 Release. Organisation for Economic Co-operation and Development, Available at http://oe.cd/icio.

OECD, 2021b. Trade in embodied CO2 (TeCO2) Database. Organisation for Economic Co-operation and Development, Available at http://oe.cd/io-co2.

Peters, G.P., 2008a. From production-based to consumption-based national emission inventories. Ecol. Econom. 65 (1), 13–23.

Peters, G., 2008b. Reassessing carbon leakage. In: Eleventh Annual Conference on Global Economic Analysis, "Future of Global Economy". Helsinki, Finland, June 12-14, 2008.

Peters, G.P., Hertwich, E.G., 2008. Post-kyoto greenhouse gas inventories: Production versus consumption. Clim. Change 86 (1), 51–66.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. Proc. Natl. Acad. Sci. USA 108 (21), 8903–8908.

Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2007. China's growing CO2 emissions: A race between increasing consumption and efficiency gains. Environ. Sci. Technol. 41 (17), 5939–5944.

Quéré, C.L., Korsbakken, J.I., Wilson, C., Tosun, J., Andrew, R., Andres, R.J., Canadell, J.G., Jordan, A., Peters, G.P., Vuuren, D.P.v., 2019. Drivers of declining CO2 emissions in 18 developed economies. Nat. Clim. Chang. 9 (3), 213.

Taylor, M.S., 2005. Unbundling the pollution haven hypothesis. B. E. J. Econ. Anal. & Policy 4 (2).

Wood, R., Grubb, M., Anger-Kraavi, A., Pollitt, H., Rizzo, B., Alexandri, E., Stadler, K., Moran, D., Hertwich, E., Tukker, A., 2019. Beyond peak emission transfers: Historical impacts of globalization and future impacts of climate policies on international emission transfers. Clim. Policy 1–14.

Wu, R., Ma, T., Schröder, E., 2022. The contribution of trade to production-based carbon dioxide emissions. Struct. Change Econ. Dyn. 60, 391–406.

Xu, Y., Dietzenbacher, E., 2014. A structural decomposition analysis of the emissions embodied in trade. Ecol. Econom. 101, 10–20.

Yamano, N., Guilhoto, J., 2020. CO2 emissions embodied in international trade and domestic final demand: Methodology and results using the OECD inter-country input-output database. OECD Science, Technology and Industry Working Papers, Organisation for Economic Co-operation and Development.

Zhang, Z., Zhu, K., Hewings, G.J.D., 2017. A multi-regional input–output analysis of the pollution haven hypothesis from the perspective of global production fragmentation. Energy Econ. 64, 13–23.