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The contribution of trade to production-Based carbon dioxide emissions

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ABSTRACT

International trade and emission offshoring can reduce a country's domestic carbon dioxide emissions, helping it to reach emission reduction targets set under the prevailing territorial climate policy frameworks. We ask what is the net contribution of trade to national production-based emissions. Existing metrics (consumption-based emissions and the technology-adjusted balance of emissions embodied in trade) do not answer this question. Based on global multi-regional input-output tables and the domestic technology assumption, we calculate net emission onshoring as the difference between the emissions embodied in gross exports (onshoring) and the emissions avoided by gross imports (offshoring) for 43 countries between 2000–2014. We find that the USA offshores emissions and China onshores emissions; the aggregate trade balance explains this result while the trade composition plays a negligible role in either country. In general there is no cross-country relationship between net offshoring and per-capita income, and neither one between trade specialization in emission-intensive products and per-capita income. The developed countries' absolute decoupling of economic growth and production-based emissions since 2000 is "genuine" in the sense that it reflects domestic economic developments and is not owed to emission offshoring.

1. Introduction

Importing goods and services can be viewed as a form of emission offshoring: the USA avoids emissions when foreign producers emit carbon dioxide as a by-product of satisfying American demand. Exporting goods and services can be viewed as a form of emission onshoring: American producers emit carbon dioxide as a by-product of satisfying foreign demand. When the emissions offshored exceed the emissions onshored, trade implies a net reduction in the emissions of American producers. Trade thus enables the USA to evade emission responsibility under the current climate policy frameworks, which are based on production-based (or territorial) accounting principles (e.g. Peters, 2008). In the opposite case, when emission onshoring exceeds emission offshoring, trade implies a net increase in a country's production-based emissions and makes it more challenging to reach national climate policy targets. Our goal is to assess if trade accounts for the absolute decoupling of the policy-relevant (production-based) emissions and economic growth in many developed countries since 2000.[1] To this end we measure the net contribution of trade to national production-based emissions (which we call domestic emissions). Furthermore, we investigate if trade systematically helps the developed countries evade emission responsibility under production-based accounting principles. To this end we analyze if there is a statistically significant and quantitatively important relationship between net offshoring and the per-capita income level across countries.

The mere transfer of emissions from one country to another does not help the global environment. Consumption-based carbon accounting reflects this concern and attributes all emissions along the global value chain to the final consumer, regardless

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[1] Many developed countries managed to combine production-based emission reductions and economic growth in the 21st century (see e.g. Le Quéré et al., 2019; Levin and Rich, 2017).

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of where production takes place. A country's consumption-based emissions are the global emissions "embodied" in its final demand (Ahmad and Wyckoff, 2003; Munksgaard and Pedersen, 2001; Peters, 2008). Any gap between a country's production-based emissions (PBE) and its consumption-based emissions (CBE) implies *international emissions transfers*, conventionally measured by the balance of emissions embodied in trade (BEET = PBE - CBE). Ever since global multi-regional input-output tables became available, the trends and patterns in international emission transfers are well documented (Davis and Caldeira, 2010; Hertwich and Peters, 2009; Peters and Hertwich, 2008). There is a negative cross-country relationship between the BEET and per-capita income. For the developed countries the CBE tend to be lower than the PBE, and the opposite is true for the developing countries. In 2008, the emission transfers from Annex-B countries to non-Annex-B countries exceeded the reductions achieved under the Kyoto protocol until then (Peters et al., 2011). Moreover, while the developed countries successfully reduced the Kyoto-relevant territorial emissions between 1990–2011, their CBE increased in the same period (Kanemoto et al., 2014). These facts have raised the concern that the developed countries' successful decoupling of PBE and economic growth may not be genuine – merely an apparent success that critically depends on international trade and emission offshoring.

The BEET cannot be used to appraise the decoupling experience because it does not measure the contribution of trade to domestic emissions, and because it falls when a country takes genuine climate mitigation action. When the emission intensity of production differs across countries, even the exchange of identical products of equal value implies international emission transfers (Jakob and Marschinski, 2013; Jakob et al., 2014). Improving the domestic energy intensity and decarbonizing the power sector, ceteris paribus, decreases the BEET. Countries hosting energy efficient producers and running low-carbon power systems ("green" countries) tend to show negative BEETs (prime examples are Sweden and Switzerland, developed economies that generate electricity mainly from nuclear and hydro power). The importance of international technology differences motivates technology-adjusted carbon accounting (Baumert et al., 2019; Jiborn et al., 2018; 2020; Kander et al., 2015). The idea is to eliminate the effects of international technology differences by standardizing the production technology at the world average level. When the technology adjustment is made, the clear divide between developed and developing countries disappears. There is no cross-country relationship between the *technology-adjusted* balance of emissions embodied in trade (TBEET) and per-capita income. The Anglophone developed countries (Australia, Canada, the UK, and the USA) record negative TBEETs but many European countries record positive TBEETs (Baumert et al., 2019).

The TBEET does not measure the contribution of a country's trade to domestic emissions either. The rationale for technology-adjusting the emissions embodied in exports (EEX) derives from a counterfactual no-trade scenario: "we consider what would be the case if a certain commodity were not to be exported from the country in question" (Kander et al., 2015, p. 432). The scenario takes domestic and foreign demand as given, meaning a foreign producer using foreign technology would have to produce a given commodity if the actual exporter did not produce it. As the counterfactual producer is unknown, "the most plausible, and least demanding, assumption is that a similar good would have been produced at the average emissions intensity on the world market for the relevant sector" (Kander et al., 2015, p. 432). In accordance with the counterfactual scenario, the technology-adjusted emissions embodied in exports (TEEX) have to be interpreted as a measure of the emissions avoided in the rest of the world by the focus country's exports – the TEEX measure the *foreign emissions avoided by exports*, which we regard as negative weak carbon leakage.[2]

We are interested in the net contribution of trade to *domestic* emissions. For given domestic and foreign demands, exports generate domestic emissions and imports avoid them. The emissions embodied in imports do not accurately measure the emissions avoided because the concept reflects the foreign production technology. The domestic emissions avoided by imports should reflect the domestic production technology. Following this principle, we apply domestic emission multipliers to observed import flows. Before global multi-regional input-output (MRIO) tables became available, domestic emission multipliers were commonly applied to gross trade flows in order to calculate emissions embodied in imports. When the goal is footprint analysis and the production technology differs between the trading partners, this procedure introduces an error and the error can be large (Peters and Hertwich, 2006). When the goal is to measure the emissions avoided by imports, the domestic technology assumption is a feature, not a bug. We use it to measure *emission offshoring* – the emissions domestic producers would have emitted had they used domestic technology to produce the imported products. This understanding of emission offshoring "is similar to labor offshoring, where one is concerned with the jobs lost at home rather than those created abroad" (Brunel, 2017, p. 630).

Several studies calculate the emissions avoided by imports (either local air pollution avoided or carbon dioxide emissions avoided) for single countries, country pairs, and the European Union as a whole.[3] When the concept enters a global analysis based on global MRIO tables, the investigation focuses on the relation between trade and *global* emissions: Chen and Chen (2011), Zhang et al. (2017), and López et al. (2018) test implications of the Pollution Haven Hypothesis (PHH) and assess if global trade is environmentally efficient, that is, if observed trade flows reduce global emissions relative to a hypothetical scenario without trade.[4]

We use the same concept – the emissions avoided by imports – but our goals are different. We start from the premise that production-based accounting is here to stay, and that national climate mitigation targets will continue to be defined in terms of production-based emission inventories. We investigate if the decoupling experience is a genuine success, that is, if production-based emission trends are different when emission offshoring is taken into account. After documenting individual country trends, we run cross-country regressions to analyze if net offshoring varies with per-capita income, that is, if the observed trade patterns systematically help developed countries reach their emission targets while making it difficult for developing countries. Throughout the paper we discuss whether the findings conform to the PHH's predictions or not.

Section 2 introduces key concepts, describes our methods, defines net onshoring as the emissions generated by exports (onshoring) minus the emissions avoided by imports (offshoring), and presents the data sources. Section 3 reports the main results: the

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[2] Where strong carbon leakage refers to climate policy-induced emission increases in the ROW, weak carbon leakage refers to "demand-driven" emission increases in the rest of the world (ROW) that need not have anything to do with the impact of climate policy on trade (e.g. Peters, 2010; Peters et al., 2011). Leakage originally referred to the relation between Kyoto-constrained Annex-B countries and unconstrained non-Annex B countries, while here we consider the relation between a focus country and the ROW.

[3] Ackerman et al. (2007); Arto et al. (2014); Dietzenbacher and Mukhopadhyay (2007); Ding et al. (2018); Lin and Sun (2010); Peters et al. (2007).

[4] The PHH can be viewed as an application of the theory of comparative advantage. Standard economic models predict that trade will increase global pollution relative to a no-trade scenario, and high-income countries will specialize in producing relatively clean goods (e.g. Copeland and Taylor, 1994). Taylor (2005) and Cherniwchan et al. (2017) review theory and econometric evidence in relation to the PHH.

USA offshores emissions and China onshores emissions; the overall balance of trade and not the composition of trade accounts for this result. In general there is no (statistically significant and quantitatively important) cross-country relationship between net onshoring and per-capita income. PBE are trending downward in most developed countries, also when adjusted for trade. Emission offshoring is not responsible for the developed countries' absolute decoupling of economic growth and emissions. Section 4 concludes that a key blind spot of production-based accounting is less worrisome than the standard metrics suggest.

2. Key concepts, methods, and data

We define *net onshoring* as the difference between the *domestic emissions embodied in gross exports* and the *domestic emissions avoided by gross imports*, calculated on the basis of the Emissions Embodied in Bilateral Trade (EEBT) approach. The EEBT approach lost popularity since global MRIO tables became available enabling global footprint analysis and the calculation of emissions embodied in final demand. The alternative MRIO approach defines the emissions embodied in exports (EEX) as the domestic emissions embodied in foreign final demand, and the emissions embodied in imports as the foreign emissions embodied in domestic final demand (EEM). The difference between the two approaches comes down to the treatment of the emissions embodied in intermediate inputs. Peters (2008), Minx et al. (2009), and Kanemoto et al. (2012) review the different concepts and approaches and evaluate their strengths and weaknesses. Our research goals call for the EEBT approach (see the arguments put forward by Kanemoto et al., 2012, p. 178). It is aligned with our system boundary, the national economy, and easily allows separating the effect of the overall trade balance from other proximate drivers. For a given country, the domestic emissions embodied in gross exports (EEGX) measure the domestic emissions due to producing the exported products, and the domestic emissions avoided by gross imports (EAGM) measure the domestic emissions avoided by importing products. Net onshoring, the difference between the two variables, is also known as the *balance of avoided emissions* (e.g. Arto et al., 2014).[5]

2.1. Using the input-Output model to measure emission offshoring

To explain the construction of our variables, we present the input-output model while closely following Peters' notation (Peters, 2008). x (dimension nm) is the global gross output vector and A ($nm \times nm$) is the global technical coefficients matrix, where n is the number of industries and m the number of countries. The vector $z^{rr} = A^{rr}x^r$ (n) represents the domestic intermediate inputs used by the focus country r, and the vector $z^{rs} = A^{rs}x^s$ (n) represents the domestic intermediate inputs used by the foreign country s (country r's intermediate product exports to country s). y (nm) is the world final demand vector. The sub-vector y^{rr} (n) represents country r's final demand for its own products and y^{rs} (n) represents country s's final demand for country r's products (country r's final product exports to country s). $L = (I - A)^{-1}$ ($nm \times nm$) is the global Leontief inverse, and $x = A\hat{x} + y = (I - A)^{-1}y = Ly$ (nm).

The EEBT approach uses domestic emission multipliers, which reflect the production technology, and gross trade flows, which reflect the scale and composition of trade, to construct the emissions embodied in exports and imports. Country r's gross export vector e^r (n) and its gross import vector m^r (n) include products that enter foreign intermediate consumption z and products that enter foreign final consumption y:

$$e^r = \sum_{s \neq r} e^{rs} = \sum_{s \neq r} (z^{rs} + y^{rs}) \tag{1}$$

$$m^r = \sum_{s \neq r} e^{sr} = \sum_{s \neq r} (z^{sr} + y^{sr}) \tag{2}$$

Emission intensities – the direct emissions per unit of gross output – extend the economic model. The global emission intensity vector f (nm) represents the direct emission intensities, the sub-vector vector f^r (n) the emission intensities of the focus country r. The emissions embodied in gross exports and imports are constructed as follows (see e.g. Peters, 2008):

$$EEGX^r = f^r L^{rr} \sum_{s \neq r} e^{rs} = f^r L^{rr} e^r \tag{3}$$

$$EEGM^r = \sum_{s \neq r} f^s L^{ss} e^{sr} = f^s L^{ss} m^r \tag{4}$$

where $L^{rr} = (I - A^{rr})^{-1}$ ($n \times n$) is country r's national Leontief matrix. The vector of domestic emission multipliers, $q^r = f^r L^{rr}$ (n), reflects the domestic production technology. When applied to gross exports, the multipliers give the domestic emissions embodied in gross exports, our measure of onshoring (Eq. 3). The foreign emissions embodied in gross imports (Eq. 4) poorly measure the domestic emissions avoided by imports because they reflect the foreign production technology. Substitution of the focus country's emission multipliers for the trading partners' multipliers ($q^s = f^s L^{ss}$ in Eq. 4) gives the domestic emissions avoided by gross imports (see e.g. López et al., 2018; Peters et al., 2007):

$$EAGM^r = f^r L^{rr} m^r \tag{5}$$

The difference between EEGX (onshoring) and EAGM (offshoring) measures the contribution of a country's trade to domestic emissions:

$$NONSH^r = EEGX^r - EAGM^r = f^r L^{rr} (e^r - m^r) \tag{6}$$

This is net onshoring, the balance of avoided emissions. Net trade leads to domestic emission increases when onshoring exceeds offshoring ($EEGX > EAGM$), and to decreases otherwise. The change is always relative to a counterfactual scenario in which the focus country produces the products imported but does not produce the products exported. This mirrors the no-trade scenario in which the ROW hypothetically produces the focus country's exports but does not produce the imports (e.g. Baumert et al., 2019; Jiborn et al., 2020).[6]

To relate emission offshoring to observed emission trends, we define *trade-adjusted PBE* as PBE plus the emissions offshored through gross imports minus the emissions onshored through gross exports (i.e. PBE minus the balance of avoided emissions):

$$TPBE^r = PBE^r - NONSH^r \tag{7}$$

The difference between PBE and its trade-adjusted version TPBE is due to trade.

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[5] The balance of avoided emissions does not actually represent a balance of avoided emissions. It represents a balance of observed emissions (embodied or generated) and counterfactual emissions (avoided). We use the term net onshoring to emphasize the distinction between emission onshoring and offshoring on the one hand, which relate to domestic emissions, and emission leakage on the other hand, which relates to foreign emissions.

[6] Net onshoring differs from the TBEET in several ways. The TBEET i) is based on the MRIO approach, ii) adjusts the direct emission intensities but not the production technology as represented by the technical coefficients, and iii) standardizes the emission intensities at the world average level (rather than using the technology of the export destination). We suggest to interpret the TBEET as a measure of the contribution of trade to *foreign* emissions: foreign emissions avoided by exports minus foreign emissions generated by imports. However, this interpretation is lost when the technology-adjustment is made also on the import side and the TBEET is defined as TBEET = TEEX - TEEM, as in Jiborn et al. (2018) and Baumert et al. (2019).

Developed countries with large service sectors could in principle satisfy their demand for heavy industrial goods by imports, reducing domestic emissions in this way (e.g. Nielsen et al., 2020). To what extent is net emission onshoring the result of importing products that would generate relatively large amounts of emissions when produced at home ("brown" products) while exporting products that generate low amounts of emissions ("green" products)? Dietzenbacher and Mukhopadhyay (2007) answer the question for India by comparing the domestic emissions embodied in one million rupees worth of Indian exports to the domestic emissions avoided by one million worth of imports. The first magnitude is lower than the second because India specializes in relatively green products while importing relatively brown products. We perform the same calculation, but rather than standardizing the scale of exports and imports at an arbitrary value (e.g. one million dollars), we set the value of exports equal to the value of imports. In this way a value of net onshoring can be determined for the hypothetical situation that trade is balanced. The EEGX can be decomposed into technology (domestic emission multipliers), composition, and scale:

$$EEGX^r = f^r L^{rr} c_x^r s_x^r \tag{8}$$

The scalar s_x^r represents the total value of country r's exports (scale), and the elements of the vector $c_x^r = e^r / s_x^r$ (n) represent the share of each sector in the total (composition). Now we replace the scale of exports in a given year by the scale of imports in the same year (s_m^r):

$$EEGX^r_{\text{sca-adj}} = f^r L^{rr} c_x^r s_m^r \tag{9}$$

The variable measures the amount of emissions hypothetically embodied in exports, assuming that the scale of exports adjusts to the scale of imports (meaning trade is balanced). From this we derive a scale-adjusted measure of net onshoring, which measures the net onshoring that would have occurred if trade was balanced:

$$NONSH^r_{\text{sca-adj}} = EEGX^r_{\text{sca-adj}} - EAGM^r = f^r L^{rr} (c_x^r - c_m^r) s_m^r \tag{10}$$

Scale-adjusted net onshoring can differ from zero only when the export composition c_x^r differs from the import composition c_m^r. The variable assumes positive values if brown products are exported while green products are imported, i.e. if the export composition is browner than the import composition.

Embodied emissions (EEX, EEM, EEGX, EEGM) are often the outcome of historical accounting exercises, where the input-output model serves as a tool for attributing observed emissions to consumers based on *observed* economic transactions. The emissions avoided by trade, however, are defined with respect to a *counterfactual* situation. In this case the analysis resembles an environmental impact analysis and proceeds on the back of the input-output model's structure – a causal flavor cannot be denied. Because the input-output model treats technology and demand as exogenously given, it does not capture all mechanisms that might theoretically determine a "long-run causal effect of trade on emissions" (e.g. trade leading to technology diffusion and factor reallocation will change technology and demand). The estimation of such effects would require different models and different assumptions.

2.2. Mis-Measurement and the within-Sector product mix

Emission offshoring will be mis-measured if the domestic technology assumption fails. If the chemicals industry was broadly defined and domestic producers specialized in pharmaceuticals (low energy requirements per unit output) while other chemical products (high energy requirements) were imported, applying the chemical industry's domestic emission multiplier to the imports from foreign chemical industries would lead to underestimation of the emissions avoided by imports. The measurement error from this 'aggregation problem" should shrink as the sectoral detail of the underlying MRIO increases, even if the MRIO table construction depends on fragmentary and incomplete information (Lenzen, 2011). Our data source distinguishes between pharmaceuticals and other chemical products, but the general problem remains and it occurs when within-sector differences in the product mix across countries coexist with *systematic* differences in the energy required to produce the products traded. The problem is not specific to our method but present in any study calculating the carbon emissions avoided by imports (references listed in footnote 3).

We focus on the big emitters and exclude small economies from the analysis, while reporting the full set of results in the interest of transparency. Small economies are more likely to show quantitatively important differences between exports and imports in the within-sector products mix. Coupled with the sometimes erratic behavior of the direct energy intensity and input efficiency in tiny sectors, the likelihood of mis-measurement and the relative size of the potential error are relatively greater.

Moreover, we exclude the primary industries from the analysis (and discuss the consequences of this choice in SI, Section A.1). Primary commodities produced domestically tend to differ from the primary commodities imported, because natural resources are unequally distributed across countries. While manufacturing products typically flow in two directions (e.g. Germany exports cars but also imports them), primary commodities tend to flow in one direction (e.g. Germany hardly produces crude oil but imports large amounts). The uni-directional character of trade would *magnify* the measurement error that can occur when the technology in use poorly reflects the technology needed to produce the imported commodities.

2.3. Cross-Country regressions

Do rich countries tend to offshore emissions while poor countries onshore emissions? To answer the question, we assess if per-capita income predicts net onshoring. We run cross-country regressions with net onshoring in percent of PBE as the dependent variable (y) and real per-capita income as the explanatory variable (x). We use Ordinary-Least-Squares (OLS) and data for a single year to estimate the linear conditional expectation function $\mathrm{E}(y_i|x_i) = \alpha + \beta \cdot x_i$, where i denotes the country index, α the intercept, and β the slope parameter. We also use the between estimator and the complete panel dataset to estimate $\mathrm{E}(\bar{y}_i|\bar{x}_i) = \alpha + \beta \cdot \bar{x}_i$, where $\bar{y}$ and $\bar{x}$ represent the means by country. And we use the pooled OLS estimator to estimate $\mathrm{E}(y_{it}|a_t, x_{it}) = a_t + \beta \cdot x_{it}$, where t denotes the time index and a_t year effects (the regressor vector includes year dummies). The pooled OLS regression receives most of our attention, its results should carry the greatest weight, because it exploits all the variation in the panel dataset. The regressions capture associations, the coefficients do not represent causal effects.

The somewhat unconventional regression approach requires a justification. In many branches of economics, given a short panel, the use of the within (fixed-effects) estimator is ubiquitous. The within estimator can overcome the endogeneity problem caused by unobserved heterogeneity: it is consistent for the β^c that appears in the fixed effects model $y_{it} = a_t^c + \beta^c \cdot x_{it} + c_i + u_{it}$, where u_{it} is the idiosyncratic error and the unobserved country fixed effect c_i correlates with per-capita income $\mathrm{Cov}\,(x_{it}, c_i) \neq 0$. If $\mathrm{Cov}\,(x_{it}, c_i) \neq 0$ was the only endogeneity problem, the within estimator would consistently estimate β^c and permit a causal interpretation of this parameter. Reverse causality is likely to be present as well, because if exports drive economic growth ("export-led growth"), then higher emissions embodied in exports (part of y) would seemingly drive per-capita income (x). Reverse causality calls for the 2-Stage-

Least-Squares Estimator (2SLS) to overcome the simultaneity bias and consistently estimate the structural parameter that frequently is the center of attention. Our goals, however, are different. The question "do rich countries tend to offshore emissions while poor countries onshore emissions?" can be rephrased as "how well does per-capita income predict net onshoring?" and given this question, the target of the estimation is not a structural parameter ($\beta^c =$ the causal effect of x on y), but the parameter β of the non-structural conditional expectation function that captures the linear association between x and y. Our estimators are inconsistent for β^c but consistent for β, the parameter of interest (for an elegant discussion of regression versus structure, see Goldberger, 1991, ch. 31).

With respect to inference, we follow standard practice. We do not test for heteroskedasticity but simply assume it is present and report heteroskedasticity-robust standard errors. We do not test if errors are normally distributed but rely on asymptotic theory to justify large-sample normal approximations to the distribution of the standard errors. In the pooled OLS regressions, unobserved heterogeneity implies that the errors will be correlated within countries, so the reported standard errors are heteroskedasticity- and cluster-robust (for the extension of the "Huber-White sandwich estimator" to clusters, see Rogers, 1994).

Given the discussion in the preceding section, the key regressions exclude small countries – countries whose population in the year 2000 is lower than 10 million – from the estimation sample. This choice, as well as the exact small-country threshold, is somewhat arbitrary (so are the alternatives). We explore the consequences of this choice by repeating the pooled OLS regression with alternative estimation samples (SI, Section A.3).

2.4. Data sources

We use the World Input-Output Database November 2016 Release (Timmer et al., 2015), which contains information for 56 sectors (NACE Rev.2) and 43 countries plus a model for the rest of the world from 2000–2014. The WIOD2016 represents an attractive mix of data quality, sectoral detail, and ease of use; it covers an interesting observation period stretching from the rise of China as the "factory of the world" and the emergence of large global current account imbalances to the global trade collapse in the aftermath of the Global Financial Crisis, while including several post-crisis years as well. Follow-up research may well use an alternative source, given that differences exist between the various global MRIO tables (e.g. Satoshi and Owen, 2014).

Corsatea et al. (2019) provide the associated environmental satellite accounts consistent with the WIOD's industry classification system. The environmental accounts include values for production-based (direct) CO2 emissions from fossil fuel combustion and industrial processes by country-sector-year in the period 2000–2016. In contrast to conventional energy balances, the environmental accounts follow the residency principle, road transport emissions are allocated to the producing sectors and households, and international transport emissions are allocated to the sectors air transport and water transport (see Corsatea et al. 2019 for details). At the global level in 2014, the primary sector (industry codes A and B) accounts for 5.3% of total PBE, the industry sector (C, E, and F) for 29.1%, the service sector (G to U) for 14.3%, the energy sector (D) for 39.7%, and households for 11.6%.

We supplement the environmentally-extended IO tables with country-level population and national accounts data from the Penn World Table Version 9.1 (Feenstra et al., 2015). As an indicator of income per capita, we use output-side real GDP at chained PPPs in 2011US$ divided by population.

The final data set covers 43 countries between 2000–2014 (SI, Table 3 reports summary statistics). In 2014 the 43 countries make up 85.6% of global GDP, 63.3% of the global population, and 78.6% of global carbon dioxide emissions. The replication package is available at the Harvard Dataverse (Wu et al., 2022).

3. Results and discussion

3.1. Offshoring in major economies

We begin with the analysis of emission offshoring trends in the six biggest OECD countries (the G7 minus Canada) and the two biggest developing countries (China and India). The USA is net offshoring emissions throughout the study period from 2000–2014, meaning the country benefits from trade in the sense that trade reduces its policy-relevant emissions (Fig. 1). The scale of net emission offshoring is considerably smaller than the scale of emission transfers as measured by the conventional balance of emissions embodied in trade. The BEET exceeds −1 Gt before the Global Financial Crisis and stays at about −800 Mt since then, while net onshoring amounts to −200 or −250 Mt in the early years of the 21st century and to roughly −100 Mt in the post-crisis period.

China is the mirror image of the USA, onshoring emissions throughout the study period. The amounts in the early 2000s are negligible, so our results essentially confirm there is "a rough balance between CO2 emissions from the production of exports and emissions avoided by imports" (Peters et al., 2007, p. 5941) at the time of China's WTO accession. China really begins to onshore emissions after 2003, in tandem with the rising trade surplus, and emerges as the world's largest "carbon haven" (defined as a country where net onshoring is positive). Net onshoring (i.e. the balance of avoided emissions) peaks at more than 500 Mt before the crisis and stays slightly below 500 Mt thereafter, which is approximately one third of the amount of emissions transfers.

The USA's emission offshoring and China's onshoring is driven by the balance of trade and has little to do with the composition of trade. Scale-adjusted net onshoring measures the onshoring that would have occurred if trade was balanced, assuming that exports adjust to the level of imports. If the USA exported more and China less, offshoring would be negligible in either country (Fig. 1). The scale-adjusted offshoring measure is not driven by cross-country differences in the trade composition but by within-country differences between the export composition and the import composition. For the USA and China, this difference is too small to matter for emission offshoring. The USA offshores emissions because it runs trade deficits and China onshores emissions because it runs trade surpluses, not because the countries specialize in green or brown products.

Germany and Japan record negative emission balances just like the USA, but unlike the USA, they are onshoring emissions throughout the study period. The BEET is negative while net onshoring is positive. The scale of emission onshoring is similar in both countries, but the proximate drivers are different. Germany onshores emissions because it runs large, structural trade surpluses before and after the crisis, while the trade composition plays a negligible role. Japan runs moderate trade surpluses in the 2000s that turn into moderate deficits after the crisis. It tends to export brown products while importing green products, even more so after the crisis than before.

Although India's BEET is positive, the country is in fact offshoring emissions since 2000. Dietzenbacher and Mukhopadhyay (2007) reject the characterization of India as a carbon haven based on data from the 1990s, and we confirm this result for the period 2000–2014. Throughout the study period India exports relatively green products while importing relatively brown products. The UK is offshoring emissions, but the amounts are modest and significantly smaller than the UK's international emission transfers. France and Italy show the same patterns: the countries are trans-

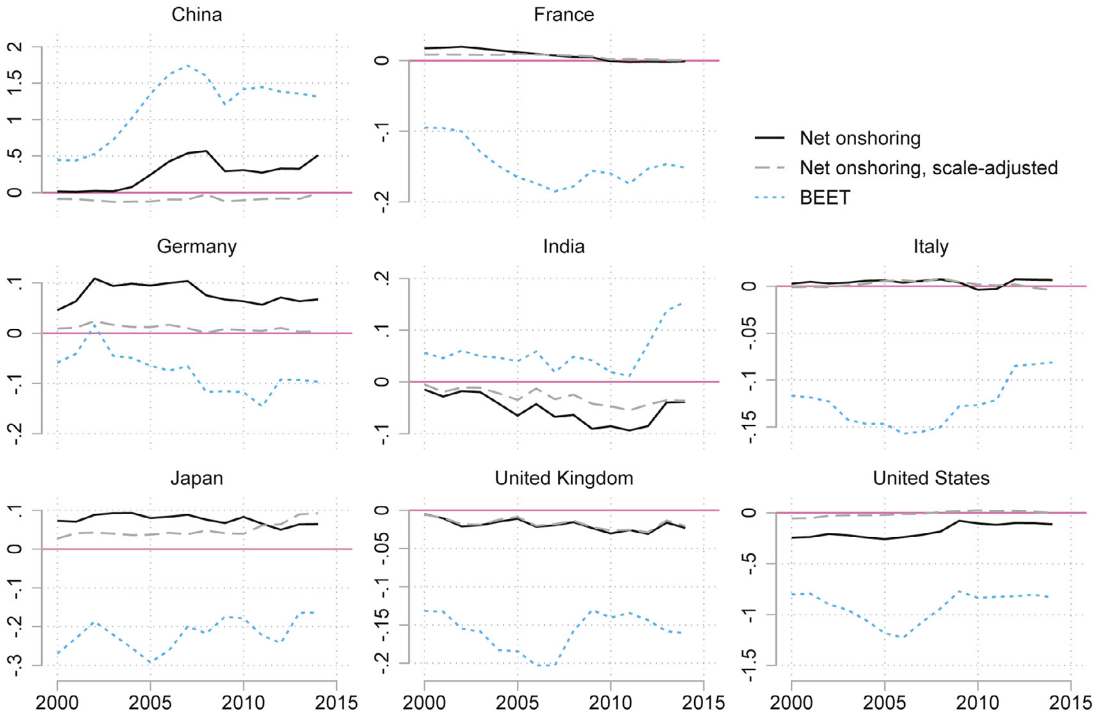

Fig. 1. Net Onshoring (Balance of Avoided Emissions) in Eight Large Economies 2000–2014 Notes: Own calculations based on WIOD2016. Net onshoring (the balance of avoided emissions) is the difference between the domestic emissions embodied in gross exports (onshored emissions) and the domestic emissions avoided by gross imports (offshored emissions). Scale-adjusted net onshoring measures the net onshoring that would have occurred if trade was balanced, assuming that exports adjust to the level of imports. The conventional balance of emissions embodied in trade (the emissions embodied in exports minus emissions embodied in imports) is shown for comparison. All variables are measured in Gt.

ferring emissions to the ROW, but net onshoring is near zero and negligible.

3.2. Trade-Adjusted PBE

Are national emission trends any different when offshoring is taken into account? We define trade-adjusted PBE as PBE plus the emissions offshored through gross imports minus the emissions onshored through gross exports (Eq. 7). The largest developed economies have managed to reduce their PBE in the 21st century (Fig. 2). In five out of the six developed countries shown, emissions peak before trade and production collapse in the aftermath of the Global Financial Crisis. The trade-adjusted measure essentially shows the same pattern. The net contribution of emission offshoring is too small to significantly change the observed trends.

Trade-adjusted PBE are rising in the five middle-income developing countries in our sample (Brazil, China, India, Indonesia, and Mexico; Fig. 2 and SI, Table 4). Trade-adjusted PBE are also rising in three high-income economies with comparative advantages in primary commodity production (Australia, Canada, Norway), three high-income economies in Asia, two Eastern European economies, as well as Malta, Russia, and Turkey. Trade-adjusted PBE are falling everywhere else (in 26 out of 43 economies in our sample). 24 of these achieve absolute decoupling of economic growth and trade-adjusted emissions (Italy and Greece do not decouple in absolute terms because their real GDP in 2014 is slightly lower than in 2000).

The first studies using global MRIO tables documented the emission trends and cross-country patterns until the Global Financial Crisis, or shortly thereafter, relative to the base year 1990 or 1995.[7] For many developed countries and regions it was true then that PBE decreased while CBE increased. More recent studies use MRIO tables covering longer stretches of the 21st century, and they document CBE reductions in many developed countries, especially since 2006. International emission transfers from the developed countries to the developing countries peak around 2006, and China's emission transfers are roughly flat since the Global Financial Crisis (Pan et al., 2017; Wood et al., 2020). The European Union's consumption-based emissions peak in 2006 (Karstensen et al., 2018; Wood et al., 2019). Le Quéré et al. (2019) identify 18 countries, all developed and including the USA, whose PBE and CBE both significantly decrease between 2005–2015. Jiborn et al. (2020) document emission reductions in 21 economies between 2000–2014 not only for the conventional PBE and CBE, but also for the technology-adjusted consumption-based emissions, defined as TCBE = PBE - TBEET. In sum, recent MRIO tables show absolute decoupling of emissions and economic growth in many developed countries regardless of metric.

We focus on net onshoring because the existing metrics are not designed to assess the extent to which trade helps or hinders the decoupling of economic growth and domestic emissions. "United Kingdom and Poland are perhaps the most striking cases for how outsourcing emissions-intensive production has helped countries meet their targets. Both countries report reductions that exceed their Kyoto targets, however once emissions embodied in their [net] imports are included, they no longer achieve these targets" (Kanemoto et al., 2014, p. 53). This statement refers to the period 1990–2011 in which PBE decrease while CBE increase; in other words, both economies meet the policy-relevant target but fail to reduce CBE emissions, which is a different target. The situation begs the question how the policy-relevant variable would have evolved if no emissions were onshored or offshored, but the CBE and the BEET do not answer it. Jiborn et al. (2018), Baumert et al. (2019), and Jiborn et al. (2020) assess the decoupling of economic growth and the technology-adjusted CBE, and

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[7] Davis and Caldeira (2010); Hertwich and Peters (2009); Kanemoto et al. (2014); Peters and Hertwich (2008); Peters et al. (2011).

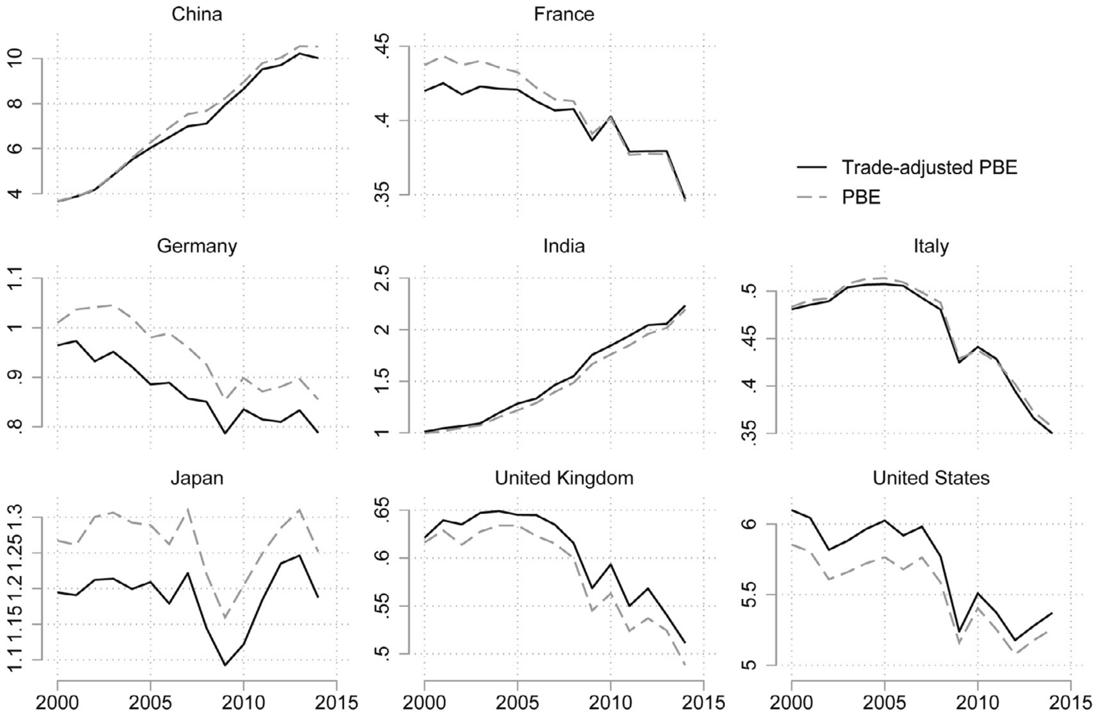

Fig. 2. Trade-Adjusted PBE in Eight Large Economies 2000–2014 Notes: Own calculations based on WIOD2016. Trade-adjusted PBE are defined as PBE plus offshored emissions minus onshored emissions (i.e. PBE minus the balance of avoided emissions). The variables are measured in Gt.

their analysis involves subtracting the TEEX from the PBE. We assess the decoupling of economic growth and the policy-relevant variable instead, and given this goal no technology-adjustment is warranted on the export side.

3.3. *Offshoring vs. income, cross-Country evidence*

Do developed countries systematically offshore emissions and developing countries onshore emissions? A visual inspection of the cross-country evidence (Fig. 3, Panels 1 and 2) shows that the answer is no. When net onshoring is plotted against the per-capita income level, there is a *positive* relationship between the two variables. As the idiosyncratic features of small countries generate distraction, we prefer to exclude them from the analysis (as discussed in Sections 2.2 and 2.3), and the attention should be focused on the large countries (Panel 2). The USA is offshoring emissions, but other developed economies are onshoring emissions (e.g. Germany, Japan, Netherlands). China is onshoring emissions, but other developing countries are offshoring emissions (Mexico, India, Indonesia). The positive net onshoring-income relationship is rather loose, and the large variation around the best linear fit suggests that many factors other than income influence net onshoring. The income level poorly predicts whether trade increases or decreases a country's PBE.

Conventional emission balances are plotted for comparison and contrast (Fig. 3, Panels 3 and 4). The USA shows negative emission balances and China shows positive emission balances, and the two countries are examples of a systematic pattern: there is a negative relationship between the BEET and income. The negative relationship is well-known and documented (e.g. Davis and Caldeira, 2010; Peters et al., 2011) and its main proximate cause are international differences in the emission intensity (Baumert et al., 2019; Jakob and Marschinski, 2013). The low emission intensities in the developed countries and the high intensities in the developing countries imply international emission transfers from the former to the latter. Given the large variation around the best linear fit, the strength of the BEET-income relationship should not be overestimated (e.g. Brazil shows a negative emission balance while South Korea shows a positive one).

Cross-country regressions of net onshoring on income complement the eyeball analysis (Table 1).[8] The upward-sloping lines in Fig. 3 are derived from simple OLS regressions based on data from 2014 (Table 1, Columns 1 and 2). The size of the regression coefficient shrinks when small countries are excluded from the estimation sample; neither coefficient is statistically significant at the 5% level. The between estimator and pooled OLS produce statistically significant slope parameters (1% level), but these results are owed to observations from small countries (Columns 3 and 5). We prefer to exclude the small countries and we regard the pooled OLS regression as the most important (Column 6): it suggests there is essentially no relation between offshoring and income. Regardless of which sample and estimation method is used, the R-squares are always low. Per-capita income poorly predicts the direction and scale of emission offshoring. Trade does not systematically inflate the developing countries' PBE or deflate the developed countries' PBE.

3.4. *Offshoring vs. income if trade was balanced, cross-Country evidence*

Given the domestic technology assumption, the scale and composition of exports and imports determine offshoring patterns. This final section focuses on the trade composition because it plays a central role in the PHH. The PHH predicts that high-income countries with relatively strict environmental standards will specialize in producing green products; if true, this would imply a correlation between net onshoring and per-capita income, a hypothesis worth checking.[9] The PHH is a product of the pure theory of trade, and

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[8] SI, Section A.2 reports regressions with BEET as the independent variable.

[9] The PHH also predicts that trade will increase global pollution relative to a no-trade scenario. Using the input-output model and global MRIO tables,

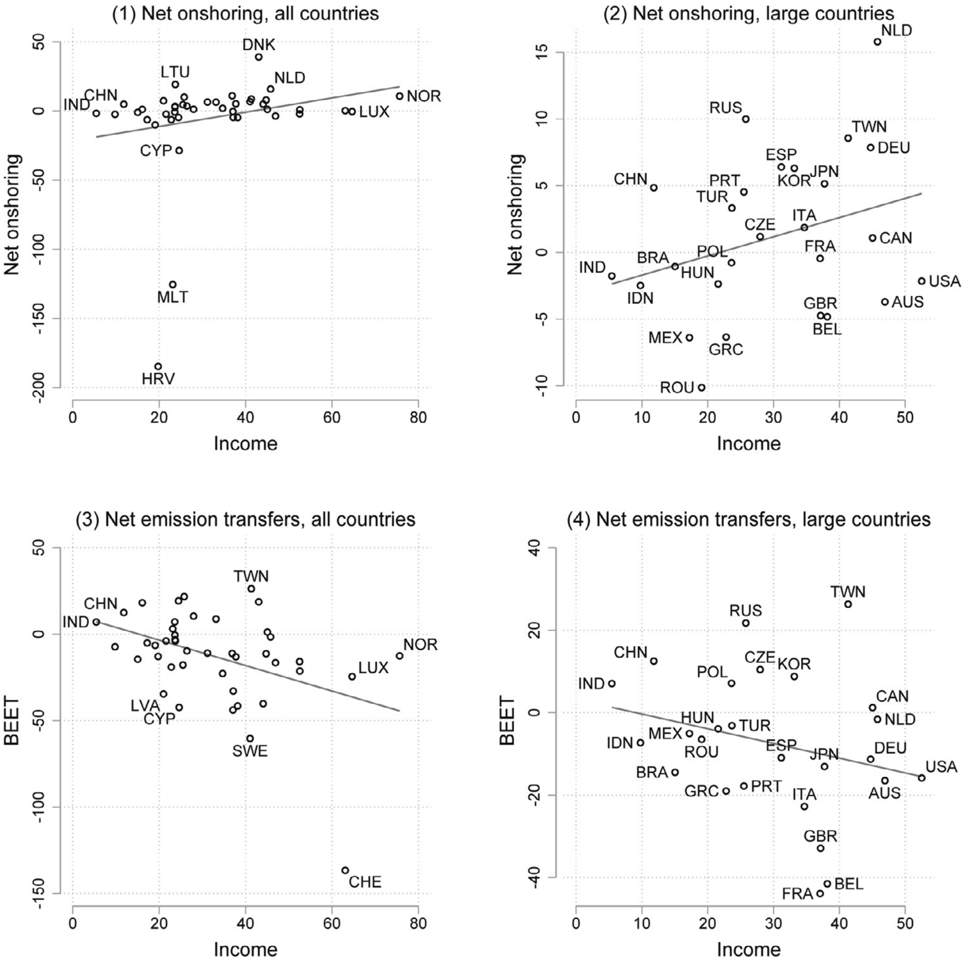

Fig. 3. Net Onshoring (Balance of Avoided Emissions) and Net Emission Transfers vs. Income, 2014 Snapshot Notes: Own calculations based on WIOD2016 and PWT9.1. The points represent the values from 2014, and the lines represent the best linear fit from simple OLS cross-country regressions. The plots 1 and 2 show net onshoring (the balance of avoided emissions) measured as the difference between the domestic emissions embodied in gross exports (onshored emissions) and the domestic emissions avoided by gross imports (offshored emissions). The plots 3 and 4 show international emission transfers (the balance of emissions embodied in trade) measured as the difference between the emissions embodied in exports and emissions embodied in imports. Emissions are expressed in percent of PBE. Income is PPP-adjusted GDP per capita in thousand 2011US$. The plots 2 and 4 exclude countries whose 2000 population is lower than 10 million.

Table 1
Net Onshoring (Balance of Avoided Emissions) vs. Income, Regressions.

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS_ALL	OLS_BIG	BTW_ALL	BTW_BIG	POLS_ALL	POLS_BIG
Income	0.517	0.144	0.483**	0.120	0.482**	0.115
	(0.289)	(0.0940)	(0.166)	(0.0925)	(0.169)	(0.0901)
Constant	-21.63	-3.142	-15.64*	-1.827	-20.49*	-2.271
	(14.25)	(2.677)	(6.879)	(2.666)	(10.06)	(2.760)
Time effects	No	No	No	No	Yes	Yes
N	43	26	645	390	645	390
R2	0.049	0.093	0.103	0.077	0.065	0.071

Notes: Own calculations based on WIOD2016 and PWT9.1. Regressions of net onshoring in percent of production-based emissions on real per-capita income in thousand international dollars. Standard errors in parentheses: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. The columns 1–2 are based on OLS and the 2014 cross-section; the standard errors are heteroskedasticity-robust (Huber-White). The columns 3–4 are based on the between estimator and the 2000–2014 panel; the standard errors are heteroskedasticity-robust (bootstrapped). The columns 5–6 are based on the pooled OLS estimator and the 2000–2014 panel; the regression constant reflects the 2014 year effect; the standard errors are heteroskedasticity- and cluster-robust (extension of Huber-White). The regressions 2, 4, and 6 exclude countries whose 2000 population is lower than 10 million.

Table 2
Scale-Adjusted Net Onshoring vs. Income, Regressions.

	(1) OLS_ALL	(2) OLS_BIG	(3) BTW_ALL	(4) BTW_BIG	(5) POLS_ALL	(6) POLS_BIG
Income	0.363	0.0651	0.221	0.0655	0.237	0.0725
	(0.286)	(0.0517)	(0.136)	(0.0481)	(0.145)	(0.0419)
Constant	-19.15	-2.826	-8.653	-1.192	-15.06	-3.048
	(14.12)	(1.810)	(6.127)	(1.648)	(9.534)	(1.495)
Time effects	No	No	No	No	Yes	Yes
N	43	26	645	390	645	390
R2	0.026	0.035	0.028	0.029	0.039	0.055

Notes: Own calculations based on WIOD2016 and PWT9.1. Regressions of scale-adjusted net onshoring in percent of production-based emissions on real per-capita income in thousand international dollars. Standard errors in parentheses: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. The columns 1–2 are based on OLS and the 2014 cross-section; the standard errors are heteroskedasticity-robust (Huber-White). The columns 3–4 are based on the between estimator and the 2000–2014 panel; the standard errors are heteroskedasticity-robust (bootstrapped). The columns 5–6 are based on the pooled OLS estimator and the 2000–2014 panel; the regression constant reflects the 2014 year effect; the standard errors are heteroskedasticity- and cluster-robust (extension of Huber-White). The regressions 2, 4, and 6 exclude countries whose 2000 population is lower than 10 million.

Table 3
Summary Statistics.

	mean	N	min	p10	p25	p50	p75	p90	max
Full sample:									
Net onshoring	-1.9	645	-334.0	-10.2	-3.7	1.2	6.7	12.5	43.9
Net onshoring, scale-adj.	-2.4	645	-329.7	-6.8	-2.9	0.4	4.4	9.1	44.6
Income per capita	28.5	645	2.0	10.4	17.1	26.8	37.6	46.5	83.9
Small countries excluded:									
Net onshoring	1.3	390	-14.7	-5.7	-2.8	1.0	5.5	9.0	22.9
Net onshoring, scale-adj.	0.5	390	-10.3	-4.7	-2.5	-0.2	2.2	4.9	44.6
Income per capita	26.1	390	2.0	8.4	15.2	26.5	36.0	42.3	52.5

Notes: Own calculations based on WIOD2016 and PWT9.1. Net onshoring (the balance of avoided emissions) in percent of PBE, and income per capita in thousand 2011US$. Small countries are those with 2000 populations lower than 10 million.

the pure theory of trade considers theoretical situations of long-run equilibrium where monetary trade imbalances are notably absent. The standard models produce balanced trade by design, and the predictions rest on trade-induced changes in the composition of economic activity (e.g. Copeland and Taylor, 1994). The scale-adjusted measure of net onshoring is therefore better suited for investigating if observed trade patterns align with the comparative advantage in emission-intensive production.

It turns out there is a *positive* cross-country relationship between scale-adjusted net onshoring and per-capita income (Fig. 4). The relationship is not statistically significant at the five-percent level, in neither regression (Table 2). The income level does not predict whether a country's trade composition reduces domestic emissions or raises them, meaning the "Green Leontief Paradox" is alive and well (Dietzenbacher and Mukhopadhyay, 2007). This result is not surprising, given the PHH's poor empirical track record. While it is true that the costs of adhering to environmental regulations can influence trade and foreign direct investment in some pollution- and energy-intensive activities, careful econometric analysis that takes into account the potential endogeneity of the main explanatory variable, as well as high-quality micro-data on establishments, firms or narrowly defined industries, are required to uncover these "pollution haven effects" (see the references in Cherniwchan et al., 2017). The effects are confined to a small segment of economic activity and play essentially no role in the determination of the sector-level trade composition.

4. Conclusions and reflections

The BEET compares *domestic* emissions generated by exports and *foreign* emissions generated by imports. As such it reveals little about the net contribution of trade to domestic emissions. We suggest to interpret the TBEET as the *net* contribution of trade to *foreign* emissions, for it compares the foreign emissions avoided by exports and the foreign emissions generated by imports. We focus on *domestic* emissions and measure net onshoring as the difference between the domestic emissions generated by exports and the domestic emissions avoided by imports. The analysis of this variable suggests that trade does not account for the advanced-economy emission reductions after 2000. In net terms and relative to PBE, the scale of emission offshoring is small.

The scale of emission offshoring is unlikely to grow in the future, because no government would deliberately promote emission offshoring as a means towards reaching national mitigation targets. Quite the opposite: economic policies targeting macroeconomic and financial stability and industrial development effectively discourage emission offshoring and promote emission onshoring instead. Macroeconomic policy makers prefer trade surpluses over deficits in order to maintain the health of domestic balance sheets and preserve financial stability, and because surpluses leave room for running expansionary monetary and fiscal policies to fight unemployment in the event of an economic downturn. Many emission-intensive activities are capital-intensive and characterized by high labor productivity, hence they have the capacity to provide well-paying jobs and belong to the set of activities which industrial policy seeks to nurture, in both the developing and the developed world. "Import substitution" development strategies may haven fallen out of favor, but to this day

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Zhang et al. (2017) and López et al. (2018) assess the environmental efficiency of trade in order to evaluate this hypothesis, and they do not find evidence supporting it.

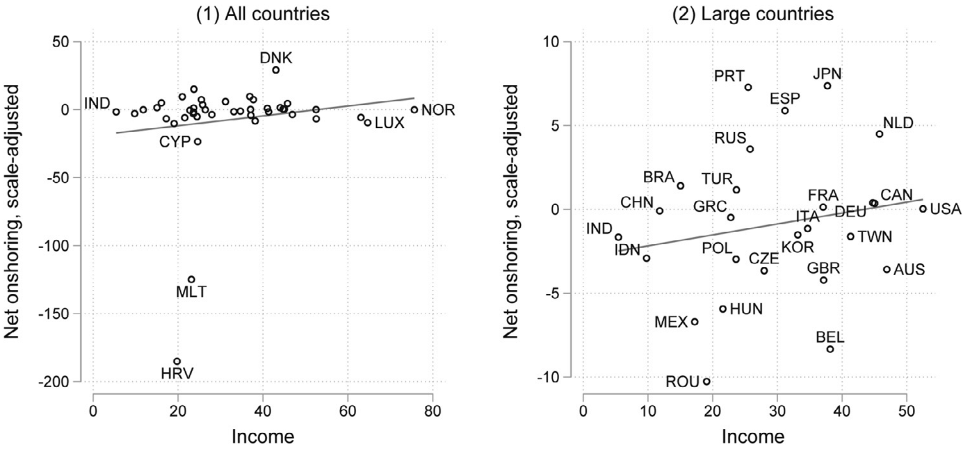

Fig. 4. Scale-Adjusted Net Onshoring (Balance of Avoided Emissions) vs. Income, 2014 Snapshot Notes: Own calculations based on WIOD2016 and PWT9.1. Scale-adjusted net onshoring is expressed in percent of PBE. It measures the net onshoring that would have occurred if trade was balanced, assuming that exports adjust to the level of imports. Income is PPP-adjusted GDP per capita in thousand 2011US$. The lines represent the best linear fit from simple OLS cross-country regressions (Table 2, Columns 1 and 2). Plot 2 excludes countries whose population in 2000 is lower than 10 million.

governments pursue "export orientated" strategies focused on the manufacturing sector in order to reach their development goals (e.g. Razmi, 2007; Rodrik, 2014). Emission offshoring takes place nonetheless, but its scale is limited by the pursuit of conventional economic policy goals.

Some productive activity moved from the advanced economies to the emerging economies and now generates emissions there while satisfying advanced-economy demand. But attention paid to the relocation of emissions in the wake of the relocation of production should not come at the expense of research and debate over the cleanup of the production still taking place in the advanced economies. Too much attention on trade can distract from the analysis and the control of the developments within national boundaries that really matter. We suggest to regard production-based emission trends as being chiefly dependent on national economic developments and mitigation efforts rather than trade. It is good news that 18 developed countries managed to improve energy intensity and expand renewable energy capacity between 2005–2015 at a pace sufficient for bringing about reductions in both PBE and CBE (Le Quéré et al., 2019). This "peak-and-decline group" demonstrates that policies promoting energy efficiency and renewable energy can generate absolute decoupling, even without recourse to emission offshoring. That said, the pace of decoupling is far from sufficient, because even the actions taken by the most successful decouplers in a low-growth environment that includes the Global Financial Crisis fall short of what is needed for climate stabilization at 2 °C above the pre-industrial baseline, let alone at 1.5 °C.[10]

We have focused on the PBE because it is the policy-relevant variable and we see little political momentum for change in international climate accounting. With regard to the normative debate about the allocation of emission responsibility[11], we have shown there is no cross-country relationship between offshoring and per-capita income – the advanced economies do not systematically evade their production-based emission responsibility. This does not imply that production-based accounting is fair. The choice of the accounting standard has distributional consequences, e.g. the typical developing country shoulders more emission responsibility under production-based accounting than it would under consumption-based accounting. While concerns about equity and justice in global mitigation efforts are thoroughly justified, it is questionable whether a change of accounting standards would be the right instrument to address them. Compared to alternative standards, production-based accounting is simple and transparent, compiling the relevant data is straightforward, the result does not depend on IO model assumptions and global MRIO tables, and a country's emission responsibility is aligned with the scope of its jurisdiction.

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. Supporting Information

The Contribution of Trade to Production-Based Carbon Dioxide Emissions

Ran Wu, Tao Ma, and Enno Schrüder

A1. The consequences of excluding the primary industries

We exclude from our analysis the emissions embodied in the primary industries' exports and imports (for the reasons, see Section 2.2). The consequences of this choice for the scale and direction of net onshoring are non-negligible but limited, and they do not challenge our main results and conclusions. The consequences can be significant for small economies that hardly produce primary commodities themselves while importing large quantities and for natural resource-abundant economies that produce large quantities for the world market. Including the primary sector does not change the emission trends in the six large developed economies, though Japan might be an exception (compare Fig. 2 to Fig. 5). Japan's increased reliance on imported fossil energy carriers in the aftermath of the Fukushima nuclear disaster probably explains the marked increase in trade-adjusted emissions

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[10] Economic growth in the peak-and-decline group was meager between 2005–2015 compared both to the developing countries and own historical standards. The median emission reduction in the peak-and-decline group was −2.4 %/yr (Le Quéré et al., 2019, Table S1), but global rates of −6 %/yr are needed after 2019 for a 66% chance of stabilizing at 2 °C. The −6 %/yr is based on Raupach et al. (2014) and taken from Robbie Andrew's website (https://folk.universitetetioslo.no/roberan/t/global_mitigation_curves.shtml). Yet unproven negative emission technologies deployed at scale would flatten the required mitigation curves, but this technological promise makes the challenge no less monumental.

[11] Afionis et al. (2017); Dietzenbacher et al. (2020); Jakob et al. (2021); Rodrigues et al. (2006); Steininger et al. (2014).

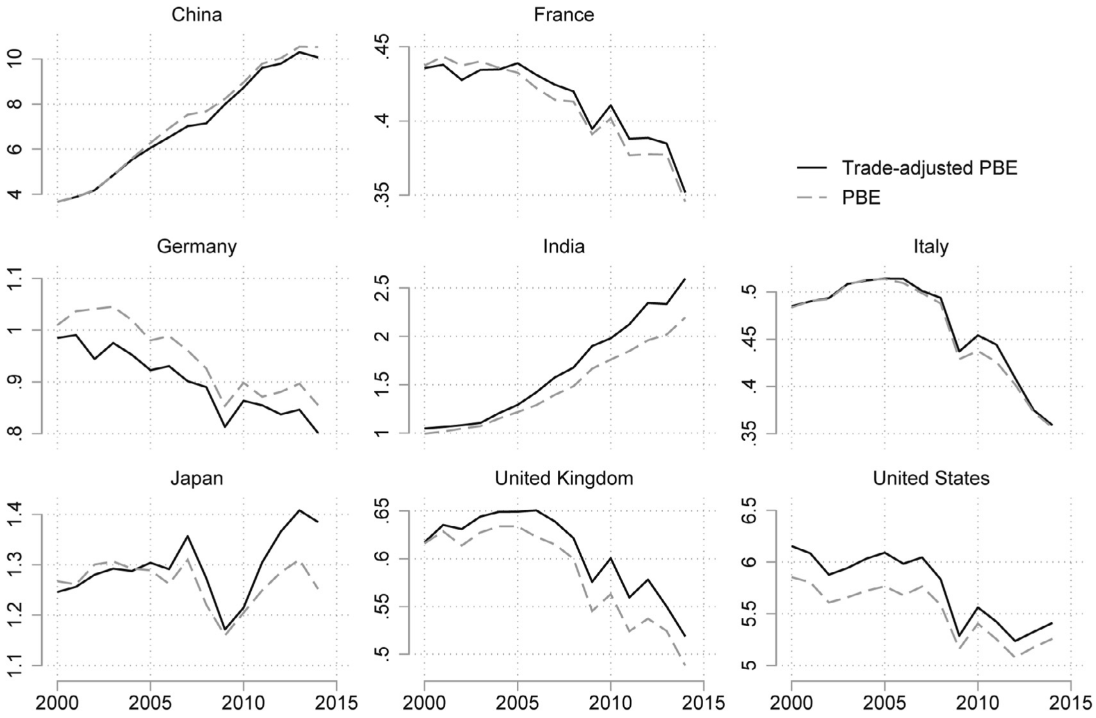

Fig. 5. Trade-Adjusted PBE in Eight Major Economies 2000–2014, Including the Primary Sector's Exports and Imports Notes: Own calculations based on WIOD2016. Trade-adjusted PBE are defined as PBE plus offshored emissions minus onshored emissions (PBE minus the balance of avoided emissions). The emissions embodied in and avoided by the primary sector's trade are included. The variables are measured in Gt.

after 2011 (Fig. 5). In 12 out of 43 economies, the mean deviation between the two measures (net onshoring in percent of PBE excluding the primary sector vs. including it) is larger than three percentage points. Economies tend to show either positive deviations throughout or negative deviations throughout, so taking the mean of the absolute deviations by country hardly makes a difference. Primary commodity exporters show large negative mean deviations (Canada −31.1 pp, Norway −9.6 pp, and Russia −86.1 pp) while relatively population-dense and natural resource-scarce economies show large positive mean deviations (Belgium 10.8 pp, Hungary 3.3 pp, India 122.8 pp, Japan 106.9 pp, South Korea 216.2 pp, Chinese Province of Taiwan 710.8 pp). Eight economies net onshore emissions on average between 2000–2014 when primary industries are excluded, but net offshore emissions when primary industries are included: mean net onshoring changes from 1.2% (of PBE) to −8.3% in Belgium, from 1.5% to −1.2% in Spain, from 0.2% to −0.2% in Estonia, from 1.8% to −1.0% in France, from 0.9% to −1.1% in Italy, from 6.0% to −2.5% in Japan, from 3.8% to −30.0% in South Korea, and from 7.3% to −220.9% in the Chinese Province of Taiwan.

In general the observed patterns conform to the comparative advantages in primary commodity production and are no reason for concern. Yet the values for the Chinese Province of Taiwan (and also South Korea) are implausible and challenge the domestic technology assumption. Extremely large positive deviations are problematic when a domestic emission multiplier that reflects the idiosyncratic energy and input intensity of a miniature-sized primary activity on domestic territory is applied to a large quantity of primary commodity imports, which often have a different character and are not produced at home. The problem is present in all studies that apply the domestic technology assumption to calculate the emissions avoided by imports. Extreme and sometimes implausible values for individual economies are easily overlooked when economy-level results are expressed in levels rather than in percent of PBE, and travel under the radar when economy-level results are aggregated to larger regions. For the reasons outlined in Section 2, the problem should be relatively severe in the primary sector of small economies.

A2. BEET Vs. income, cross-Country regression evidence

As expected, regressing the conventional emission balance on income yields negative regression coefficients (Table 5). The negative BEET-income relationship is statistically significant in two regressions (Columns 4 and 6). The R-squares are low, meaning the scale and direction of international emission transfers depends on many factors other than income (key proximate drivers are the carbon intensity of the domestic energy sector and the energy intensity of domestic producers, relative to trading partners). If the sample included more developing countries, we expect they would cluster in top-left quadrant of cross-country scatter plots (such as those in Fig. 3). The standard errors would shrink as a result, the regression coefficients would change in size but not sign, and the R-squares would probably increase slightly.

A3. Exploring alternatives estimation samples

Section 2.2 states our reasons for excluding small countries, but any such decision remains to some extent arbitrary. The best we can do is be transparent about the consequences. Here we use different estimation samples to repeat the pooled OLS regressions of net onshoring on per-capita income. Table 6 shows that increasing the small-country threshold (from zero to one million to five million to 10 million) produces smaller regression coefficients. The effect size is larger when small countries are excluded, but the explained variance is not. Table 7 shows the consequences of excluding one country at a time from the estimation sample. All coefficients are positive and not too different from the coefficient produced by the full sample. The results do not depend on the idiosyncrasies of a single country. The main and most important message is that there is no negative correlation between net

Table 4
Trade-Adjusted PBE.

	2000	2014	Δ Mt	Δ in %
AUS	371.8	419.9	48.1	12.9
AUT	68.3	54.5	-13.8	-20.2
BEL	128.5	102.3	-26.2	-20.4
BGR	61.6	44.6	-16.9	-27.5
BRA	348.8	578.4	229.6	65.8
CAN	479.4	570.7	91.4	19.1
CHE	49.0	44.0	-5.0	-10.3
CHN	3653.2	10017.6	6364.4	174.2
CYP	9.2	9.0	-0.2	-2.0
CZE	130.8	94.7	-36.1	-27.6
DEU	964.4	788.0	-176.4	-18.3
DNK	54.2	43.6	-10.6	-19.5
ESP	309.7	253.1	-56.6	-18.3
EST	16.9	20.5	3.6	21.4
FIN	58.2	45.7	-12.5	-21.5
FRA	419.9	347.1	-72.8	-17.3
GBR	621.2	511.5	-109.7	-17.7
GRC	126.3	83.6	-42.6	-33.8
HRV	29.0	50.8	21.8	75.0
HUN	60.0	48.7	-11.2	-18.7
IDN	317.3	556.3	239.0	75.3
IND	1009.4	2234.1	1224.7	121.3
IRL	44.4	43.7	-0.6	-1.5
ITA	480.9	349.9	-131.0	-27.2
JPN	1194.5	1187.5	-7.0	-0.6
KOR	513.2	627.7	114.5	22.3
LTU	14.8	14.4	-0.4	-2.4
LUX	9.4	8.3	-1.1	-11.8
LVA	9.0	8.1	-0.9	-10.3
MEX	437.9	519.9	82.0	18.7
MLT	3.1	8.2	5.1	163.1
NLD	165.0	150.3	-14.7	-8.9
NOR	38.1	45.6	7.5	19.7
POL	339.2	318.0	-21.1	-6.2
PRT	77.3	47.1	-30.2	-39.0
ROU	99.6	88.3	-11.3	-11.3
RUS	1233.4	1550.8	317.5	25.7
SVK	40.1	32.7	-7.5	-18.6
SVN	18.1	13.9	-4.2	-23.0
SWE	69.1	47.7	-21.3	-30.9
TUR	219.0	345.7	126.6	57.8
TWN	269.7	287.7	18.0	6.7
USA	6098.6	5370.5	-728.1	-11.9
ROW	4807.4	8602.7	3795.3	78.9

Notes: Own calculations based on WIOD2016. Trade-adjusted PBE are defined as PBE plus offshored emissions minus onshored emissions. The levels in 2000 and 2014 are measured in Mt; the changes from 2000 to 2014 (Δ) are measured in Mt or in percent of the 2000 level.

Table 5
BEET vs. Income, Regressions.

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS_ALL	OLS_BIG	BTW_ALL	BTW_BIG	POLS_ALL	POLS_BIG
Income	-0.736	-0.357	-0.432	-0.518**	-0.447	-0.529**
	(0.382)	(0.204)	(0.356)	(0.184)	(0.334)	(0.173)
Constant	11.28	3.230	0.229	7.089	1.906	8.348
	(10.28)	(5.393)	(8.725)	(4.930)	(9.187)	(5.006)
Time effects	No	No	No	No	Yes	Yes
N	43	26	645	390	645	390
R2	0.166	0.068	0.064	0.167	0.069	0.183

Notes: Own calculations based on WIOD2016 and PWT9.1. Regressions of the balance of emissions embodied in trade in percent of production-based emissions on real per-capita income in thousand international dollars. Standard errors in parentheses: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. The columns 1–2 are based on OLS and the 2014 cross-section; the standard errors are heteroskedasticity-robust (Huber-White). The columns 3–4 are based on the between estimator and the 2000–2014 panel; the standard errors are heteroskedasticity-robust (bootstrapped). The columns 5–6 are based on the pooled OLS estimator and the 2000–2014 panel; the regression constant reflects the 2014 year effect; the standard errors are heteroskedasticity- and cluster-robust (extension of Huber-White). The regressions 2, 4, and 6 exclude countries whose 2000 population is lower than 10 million.

Table 6
Pooled OLS Regressions: Varying the Large-Country Threshold.

	β	SE	t-stat	N	R2
All	0.481	0.169	2.85	645	0.065
Pop<1m	0.376	0.150	2.51	600	0.095
Pop<5m	0.221	0.116	1.90	495	0.099
Pop<10m	0.114	0.090	1.27	390	0.070

Notes: Own calculations based on WIOD2016 and PWT9.1. Regressions of net onshoring in percent of production-based emissions on real per-capita income in thousand international dollars, using on the pooled OLS estimator and the 2000–2014 panel, with heteroskedasticity- and cluster-robust standard errors. β denotes the coefficient on per-capita income, and t-stat $= \beta/\text{SE}$. The regression constant and year effects are included in the model but not reported. The first and the last row repeat the pooled OLS regressions in Table 1. The second row excludes countries whose 2000 population is lower than one million. The third row excludes countries whose 2000 population is lower than five million.

Table 7
Pooled OLS Regressions: Leave Out One Country.

	β	SE	t-stat	N	R2
AUS	0.491	0.168	2.92	630	0.066
AUT	0.478	0.168	2.84	630	0.064
BEL	0.481	0.168	2.86	630	0.065
BGR	0.476	0.177	2.68	630	0.064
BRA	0.511	0.178	2.87	630	0.069
CAN	0.480	0.169	2.84	630	0.064
CHE	0.509	0.171	2.98	630	0.068
CHN	0.521	0.180	2.90	630	0.071
CYP	0.475	0.169	2.81	630	0.064
CZE	0.483	0.170	2.83	630	0.066
DEU	0.475	0.168	2.82	630	0.063
DNK	0.436	0.164	2.67	630	0.058
ESP	0.482	0.169	2.85	630	0.066
EST	0.489	0.173	2.82	630	0.067
FIN	0.472	0.169	2.80	630	0.063
FRA	0.481	0.168	2.86	630	0.065
GBR	0.485	0.168	2.88	630	0.066
GRC	0.482	0.171	2.82	630	0.064
HRV	0.385	0.138	2.80	630	0.053
HUN	0.486	0.173	2.80	630	0.066
IDN	0.518	0.182	2.84	630	0.070
IND	0.515	0.187	2.76	630	0.068
IRL	0.511	0.169	3.03	630	0.070
ITA	0.482	0.169	2.86	630	0.065
JPN	0.478	0.169	2.83	630	0.064
KOR	0.481	0.169	2.85	630	0.065
LTU	0.485	0.174	2.78	630	0.067
LUX	0.472	0.178	2.66	630	0.059
LVA	0.491	0.175	2.80	630	0.067
MEX	0.486	0.177	2.75	630	0.065
MLT	0.393	0.141	2.80	630	0.106
NLD	0.467	0.169	2.76	630	0.062
NOR	0.437	0.188	2.33	630	0.048
POL	0.487	0.174	2.81	630	0.066
PRT	0.483	0.171	2.83	630	0.066
ROU	0.480	0.177	2.72	630	0.063
RUS	0.508	0.173	2.94	630	0.070
SVK	0.494	0.173	2.86	630	0.067
SVN	0.483	0.170	2.83	630	0.066
SWE	0.478	0.169	2.83	630	0.064
TUR	0.498	0.175	2.85	630	0.068
TWN	0.477	0.168	2.83	630	0.064
USA	0.511	0.170	3.00	630	0.069

Notes: Own calculations based on WIOD2016 and PWT9.1. Regressions of net onshoring in percent of production-based emissions on real per-capita income in thousand international dollars, using on the pooled OLS estimator and the 2000–2014 panel, with heteroskedasticity- and cluster-robust standard errors. β denotes the coefficient on per-capita income, and t-stat $= \beta/\text{SE}$. The regression constant and year effects are included in the model but not reported. In the first row, Australia is excluded from the estimation sample; in the second row, Austria is excluded; and so forth.

Table 8
Net Onshoring (Balance of Avoided Emissions).

	Share of PBE			Mt		
	2000	2007	2014	2000	2007	2014
AUS	0.011	-0.019	-0.037	4.260	-8.141	-15.010
AUT	0.065	0.079	0.049	4.716	6.273	2.822
BEL	0.025	0.025	-0.048	3.251	2.956	-4.704
BGR	-0.241	-0.139	0.011	-11.962	-8.238	0.499
BRA	0.032	0.055	-0.011	11.664	21.925	-6.031
CAN	0.091	0.052	0.011	47.942	30.227	6.270
CHE	-0.012	-0.013	0.002	-0.561	-0.630	0.074
CHN	0.004	0.072	0.049	14.456	539.751	510.994
CYP	-0.217	-0.140	-0.286	-1.643	-1.233	-2.013
CZE	0.023	-0.037	0.012	3.031	-5.033	1.134
DEU	0.045	0.108	0.079	45.599	103.689	67.274
DNK	0.292	0.439	0.390	22.375	44.390	27.875
ESP	0.006	-0.025	0.064	1.962	-9.236	17.319
EST	-0.100	0.037	-0.048	-1.534	0.749	-0.933
FIN	0.140	0.122	0.109	9.491	9.689	5.600
FRA	0.040	0.018	-0.005	17.328	7.506	-1.560
GBR	-0.008	-0.032	-0.047	-5.060	-19.660	-23.139
GRC	0.043	0.062	-0.063	5.660	8.812	-4.993
HRV	-0.421	-0.608	-1.847	-8.596	-15.271	-32.972
HUN	-0.010	-0.038	-0.024	-0.595	-2.313	-1.124
IDN	0.048	0.009	-0.025	15.903	3.687	-13.472
IND	-0.015	-0.048	-0.018	-14.880	-67.721	-38.778
IRL	-0.015	-0.093	0.008	-0.674	-4.367	0.354
ITA	0.006	0.012	0.019	2.714	5.846	6.652
JPN	0.057	0.067	0.051	72.718	88.363	64.442
KOR	0.053	0.025	0.063	28.500	14.345	42.268
LTU	-0.188	-0.067	0.191	-2.344	-1.096	3.411
LUX	0.187	0.172	-0.005	2.161	2.548	-0.040
LVA	-0.082	-0.072	0.073	-0.680	-0.749	0.639
MEX	-0.076	-0.072	-0.064	-30.898	-34.669	-31.215
MLT	0.037	-0.074	-1.255	0.121	-0.264	-4.562
NLD	0.137	0.124	0.158	26.244	23.709	28.198
NOR	0.390	0.328	0.107	24.366	22.391	5.472
POL	-0.040	-0.027	-0.008	-13.086	-9.133	-2.437
PRT	-0.142	-0.028	0.045	-9.632	-1.786	2.239
ROU	-0.021	-0.137	-0.101	-2.049	-14.532	-8.125
RUS	0.229	0.115	0.100	365.903	197.992	172.237
SVK	0.034	0.083	0.027	1.402	3.402	0.908
SVN	-0.165	-0.003	0.035	-2.551	-0.049	0.505
SWE	0.037	0.050	0.067	2.654	3.122	3.435
TUR	0.031	-0.005	0.033	7.006	-1.437	11.900
TWN	0.026	0.082	0.086	7.073	26.796	26.968
USA	-0.042	-0.038	-0.022	-244.760	-217.323	-113.082
ROW	-0.036	-0.116	-0.098	-168.640	-734.413	-767.584

Table 9
Net Onshoring (Balance of Avoided Emissions) Including the Primary Industries.

	Share of PBE			Mt		
	2000	2007	2014	2000	2007	2014
AUS	0.029	-0.003	0.002	10.936	-1.209	0.924
AUT	0.050	0.063	0.010	3.670	5.000	0.574
BEL	-0.016	-0.063	-0.152	-2.062	-7.568	-14.848
BGR	-0.267	-0.162	0.002	-13.260	-9.585	0.092
BRA	0.038	0.072	0.007	13.694	28.673	4.188
CAN	0.132	0.112	0.094	69.476	64.679	54.160
CHE	-0.020	-0.024	-0.007	-0.991	-1.130	-0.311
CHN	0.002	0.068	0.043	5.812	509.932	457.823
CYP	-0.222	-0.146	-0.289	-1.681	-1.285	-2.035
CZE	-0.022	-0.085	-0.054	-2.915	-11.511	-5.185
DEU	0.025	0.062	0.063	25.023	59.234	54.036
DNK	0.309	0.447	0.391	23.632	45.261	27.988
ESP	-0.007	-0.031	0.011	-2.108	-11.697	3.070
EST	-0.108	0.028	-0.049	-1.659	0.565	-0.957
FIN	0.103	0.088	0.080	6.979	7.039	4.096
FRA	0.004	-0.024	-0.018	1.736	-10.135	-6.335
GBR	-0.002	-0.039	-0.062	-1.138	-24.045	-30.472
GRC	0.027	0.051	-0.100	3.504	7.303	-7.843
HRV	-0.418	-0.608	-1.841	-8.547	-15.263	-32.871
HUN	-0.031	-0.102	-0.116	-1.858	-6.272	-5.539
IDN	0.088	0.059	0.001	29.337	25.203	0.382
IND	-0.054	-0.129	-0.183	-53.760	-180.044	-402.276
IRL	-0.008	-0.101	0.014	-0.346	-4.718	0.596
ITA	-0.003	-0.005	-0.007	-1.464	-2.504	-2.435
JPN	0.017	-0.036	-0.106	21.373	-46.866	-132.899
KOR	0.037	-0.192	-0.536	20.147	-112.454	-359.224
LTU	-0.208	-0.087	0.181	-2.591	-1.432	3.226
LUX	0.179	0.166	-0.015	2.071	2.464	-0.125
LVA	-0.139	-0.085	0.074	-1.150	-0.878	0.643
MEX	-0.064	-0.056	-0.048	-26.169	-26.688	-23.401
MLT	0.035	-0.077	-1.258	0.113	-0.273	-4.574
NLD	0.161	0.142	0.170	30.878	27.145	30.408
NOR	0.512	0.454	0.316	31.967	30.992	16.138
POL	-0.051	-0.035	-0.014	-16.591	-11.886	-4.374
PRT	-0.170	-0.060	0.004	-11.505	-3.854	0.209
ROU	-0.039	-0.165	-0.125	-3.778	-17.504	-10.057
RUS	0.289	0.169	0.140	462.373	289.924	240.781
SVK	0.027	0.070	0.012	1.112	2.853	0.410
SVN	-0.177	-0.013	0.024	-2.749	-0.233	0.345
SWE	0.017	0.030	0.024	1.211	1.890	1.208
TUR	0.031	-0.009	0.034	7.082	-2.923	12.005
TWN	-0.543	-2.145	-3.236	-150.345	-699.737	-1018.461
USA	-0.051	-0.049	-0.029	-300.530	-282.411	-153.680
ROW	-0.019	-0.101	-0.089	-86.495	-637.869	-695.079

Table 10
Net Onshoring (Balance of Avoided Emissions), Scale-Adjusted.

	Share of PBE			Mt		
	2000	2007	2014	2000	2007	2014
AUS	-0.007	-0.009	-0.039	-2.344	-3.659	-14.501
AUT	0.049	0.030	0.015	3.476	2.342	0.836
BEL	-0.028	-0.041	-0.086	-3.615	-4.748	-8.133
BGR	0.114	0.053	0.051	5.414	3.022	2.242
BRA	0.056	0.030	0.015	18.141	10.570	8.027
CAN	0.033	0.022	0.004	15.707	10.836	2.041
CHE	-0.046	-0.069	-0.059	-2.182	-3.191	-2.539
CHN	-0.025	-0.013	-0.001	-87.317	-94.637	-10.013
CYP	0.028	-0.072	-0.238	0.213	-0.624	-1.655
CZE	0.033	-0.068	-0.039	4.154	-8.730	-3.502
DEU	0.009	0.010	0.004	8.981	9.801	3.326
DNK	0.210	0.391	0.306	14.942	37.673	20.813
ESP	0.062	0.049	0.063	18.757	17.779	15.912
EST	0.049	0.121	-0.052	0.737	2.411	-1.010
FIN	0.033	0.059	0.101	2.131	4.567	4.944
FRA	0.020	0.021	0.001	8.447	8.189	0.449
GBR	-0.010	-0.031	-0.045	-5.776	-18.148	-20.596
GRC	0.439	0.313	-0.005	56.188	43.373	-0.384
HRV	-0.431	-0.568	-2.020	-8.058	-13.367	-33.049
HUN	0.016	-0.051	-0.063	0.885	-2.992	-2.825
IDN	-0.023	-0.023	-0.034	-6.546	-7.698	-15.826
IND	-0.005	-0.027	-0.019	-4.878	-33.532	-36.413
IRL	-0.081	-0.140	-0.070	-3.402	-6.278	-3.000
ITA	-0.002	0.010	-0.012	-0.971	4.795	-4.093
JPN	0.022	0.030	0.076	27.051	38.323	92.135
KOR	0.002	-0.012	-0.016	1.076	-7.081	-10.197
LTU	-0.105	0.014	0.153	-1.259	0.222	2.673
LUX	0.114	0.101	-0.097	1.308	1.499	-0.796
LVA	0.052	0.096	0.101	0.406	0.948	0.824
MEX	-0.085	-0.084	-0.074	-31.374	-36.040	-32.759
MLT	0.225	-0.025	-1.253	0.723	-0.088	-4.538
NLD	0.064	0.036	0.048	11.417	6.379	8.016
NOR	0.169	0.169	-0.002	9.024	9.500	-0.057
POL	0.002	-0.018	-0.031	0.523	-5.755	-9.376
PRT	0.020	0.067	0.076	1.276	4.137	3.590
ROU	0.023	-0.004	-0.106	2.101	-0.382	-8.235
RUS	0.047	0.043	0.039	67.881	67.903	61.857
SVK	0.172	0.078	-0.018	7.078	3.184	-0.606
SVN	-0.059	0.022	-0.001	-0.887	0.381	-0.013
SWE	-0.049	-0.039	0.010	-3.428	-2.357	0.483
TUR	0.006	-0.011	0.012	1.205	-3.404	4.147
TWN	-0.015	-0.001	-0.018	-3.846	-0.327	-5.086
USA	-0.010	-0.002	0.000	-54.242	-10.822	1.482
ROW	-0.008	-0.045	-0.010	-36.246	-273.298	-75.440

Table 11
Balance of Emissions Embodied in Trade (BEET).

	Share of PBE			Mt		
	2000	2007	2014	2000	2007	2014
AUS	0.034	-0.158	-0.192	12.971	-67.262	-77.665
AUT	-0.192	-0.179	-0.364	-14.006	-14.192	-20.856
BEL	-0.089	-0.253	-0.386	-11.759	-30.234	-37.702
BGR	-0.024	0.111	0.190	-1.201	6.598	8.596
BRA	-0.031	-0.073	-0.153	-11.272	-29.374	-87.794
CAN	0.078	-0.061	-0.103	41.236	-35.397	-59.170
CHE	-1.010	-1.061	-1.291	-48.965	-49.726	-56.899
CHN	0.116	0.226	0.126	426.946	1702.351	1321.586
CYP	-0.213	-0.474	-0.382	-1.614	-4.184	-2.685
CZE	0.192	0.151	0.096	25.723	20.443	9.159
DEU	-0.032	-0.036	-0.088	-32.123	-34.494	-75.584
DNK	0.122	0.244	0.180	9.302	24.724	12.840
ESP	-0.068	-0.225	-0.097	-21.187	-84.294	-26.143
EST	-0.031	0.106	0.207	-0.470	2.159	4.050
FIN	0.050	-0.023	-0.087	3.351	-1.831	-4.479
FRA	-0.189	-0.405	-0.401	-82.493	-167.801	-138.577
GBR	-0.213	-0.315	-0.311	-131.467	-193.866	-151.670
GRC	-0.044	-0.069	-0.164	-5.866	-9.777	-12.888
HRV	-0.025	-0.145	-0.133	-0.516	-3.649	-2.378
HUN	-0.036	-0.132	-0.035	-2.155	-8.062	-1.656
IDN	0.080	-0.052	-0.120	26.742	-22.042	-65.329
IND	0.050	-0.005	0.048	49.618	-6.381	105.445
IRL	-0.141	-0.432	-0.197	-6.143	-20.202	-8.665
ITA	-0.201	-0.268	-0.193	-97.406	-133.486	-68.801
JPN	-0.171	-0.115	-0.096	-216.295	-150.773	-120.370
KOR	0.126	-0.030	0.101	68.160	-17.320	67.748
LTU	-0.726	-0.409	0.023	-9.033	-6.704	0.406
LUX	0.042	0.015	-0.188	0.490	0.220	-1.553
LVA	-0.374	-0.538	-0.328	-3.107	-5.589	-2.850
MEX	-0.098	-0.109	-0.074	-39.914	-52.251	-36.148
MLT	-0.322	-0.111	0.068	-1.041	-0.395	0.246
NLD	-0.028	-0.187	-0.028	-5.314	-35.629	-4.934
NOR	0.200	-0.006	-0.317	12.509	-0.429	-16.183
POL	0.036	0.049	0.073	11.764	16.758	23.030
PRT	-0.219	-0.225	-0.137	-14.832	-14.468	-6.764
ROU	0.198	-0.020	-0.039	19.324	-2.116	-3.119
RUS	0.360	0.188	0.178	576.111	323.264	307.450
SVK	0.086	0.041	0.055	3.585	1.694	1.833
SVN	-0.256	-0.195	-0.060	-3.969	-3.450	-0.868
SWE	-0.204	-0.453	-0.575	-14.642	-28.402	-29.446
TUR	-0.111	-0.105	-0.011	-25.127	-32.842	-4.069
TWN	0.076	0.190	0.219	21.137	62.029	69.063
USA	-0.121	-0.165	-0.139	-710.045	-952.095	-731.703
ROW	0.044	0.009	-0.010	202.993	58.477	-74.505

onshoring and per-capita income, regardless of which estimation sample is used. The choice of the estimation sample matters for the size of the regression coefficient and the precision with which it is estimated, but in our view, whether the positive correlation is statistically significant is of secondary importance.

CRediT authorship contribution statement

Ran Wu: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Tao Ma:** Writing – review & editing. **Enno Schröder:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision.

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