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Price Corrected Domestic Technology Assumption—A Method To Assess Pollution Embodied in Trade Using Primary Official Statistics Only. With a Case on CO_2 Emissions Embodied in Imports to Europe

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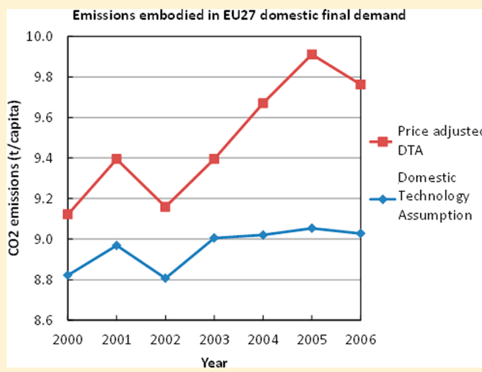
Supporting Information

ABSTRACT: Environmentally extended input output (EE IO) analysis is increasingly used to assess the carbon footprint of final consumption. Official EE IO data are, however, at best available for single countries or regions such as the EU27. This causes problems in assessing pollution embodied in imported products. The popular "domestic technology assumption (DTA)" leads to errors. Improved approaches based on Life Cycle Inventory data, Multiregional EE IO tables, etc. rely on unofficial research data and modeling, making them difficult to implement by statistical offices. The DTA can lead to errors for three main reasons: exporting countries can have higher impact intensities; may use more intermediate inputs for the same output; or may sell the imported products for lower/other prices than those produced domestically. The last factor is relevant for sustainable consumption policies of importing countries, whereas the first factors are mainly a matter of making production in exporting countries more eco-efficient. We elaborated a simple correction for price differences in imports and domestic production using monetary and physical data from official import and export statistics. A case study for the EU27 shows that this "price-adjusted DTA" gives a partial but meaningful adjustment of pollution embodied in trade compared to multiregional EE IO studies.



1. INTRODUCTION

The statistical office of the European Union, Eurostat, published in 2011 its first integrated EU27 Supply and Use Tables and Input Output Tables (SUIOT) with Environmental Extensions. The EU27 SUIOT was developed by aggregating national SUIOT reported by EU member states to Eurostat. Such tables present on a level of 59 products and 59 industries all transactions in the European economy (i.e., the intermediate use of products by domestic industry, the final use by households, government, capital formation, and exports, and the supply of products by domestic industry and imports). Data for about 8 emissions to air, mainly greenhouse gases (GHG), are available in the same industry format from (voluntary) Air Emissions Accounts.[1] They were added to the SUIOT, creating an EE SUIOT (Figure 1). Time series are available from 2000 to 2006. The construction of these tables was done by Eurostat, other EU services, and the authors.[2]

EE SUIOT have become a popular tool to estimate the life cycle environmental impacts of final consumption expenditure in a country or region. First, since the SUIOT contain all transactions in an economy, one can calculate for a specific final consumption category which industry sectors contributed which part of the final impact. Second, the EE SUIOT also give emissions by industry (and hence emissions by unit turnover). This allows calculating for each final demand/product category in the SUIOT how much emissions take place over its product life cycle (for mathematical details, we refer to the textbooks of, for example, Ten Raa[3] and Miller and Blair[4]).

A country EE SUIOT gives, however, no information on how imported (intermediate and final) products are produced and the associated emissions caused. Accounting for such "pollution embodied in imports" is highly relevant. For various countries, it has been shown that apparent decoupling of CO_2 emissions or primary material use from GDP growth is actually the result of the relocation of material and energy-intensive production abroad.[5−7]

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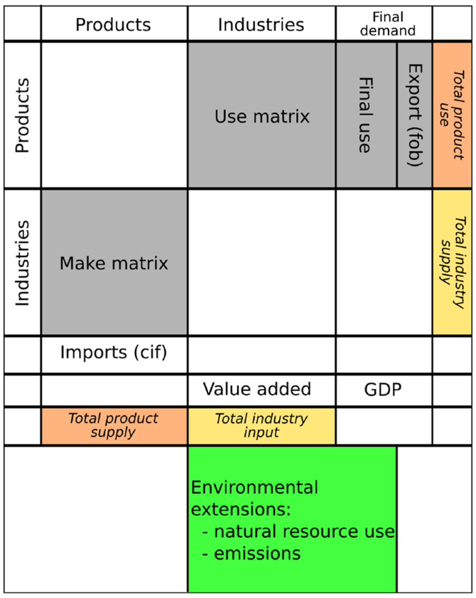

Figure 1. Schematic Supply and Use Table (SUT) with environmental extensions.

2. OPTIONS FOR CORRECTING FOR POLLUTION EMBODIED IN TRADE

Practitioners have sought to resolve this problem for imports in EE IO tables mainly via the following approaches (see, e.g., refs 8 and 9):

1. Domestic Technology Assumption (DTA). This option is popular, because it assumes that imports are made with domestic technology. It, hence, just needs the data in the existing EE SUIOT to make an estimate. However, this method can lead to erroneous results, since cradle to gate impacts of production abroad may differ from the cradle to gate impacts of production of the same products produced domestically.[10−16] Figure 2 shows the results of the DTA as applied in the Eurostat project. It suggests that the CO_2 emissions in imports and exports of the EU27 are similar (1.7 versus 1.6 ton per capita). Studies calculating impacts of imports using specific data for non-EU countries showed major differences, up to 3 ton per capita, however.[17,18]

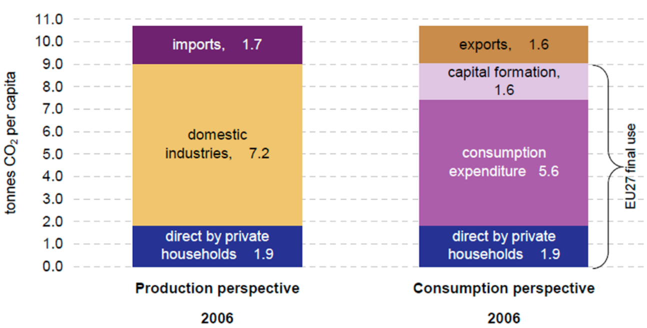

Figure 2. Carbon footprint in ton CO_2 per capita for the EU27 from a production and consumption perspective, 2006, using the Domestic Technology Assumption.[22].

2. Applying Life Cycle Inventory (LCI) Data for Imports. A practitioner may use LCI databases to estimate the impacts in the life cycle of imported products (e.g., ref 19). LCI data are mostly available for European, U.S., and Japanese processes, with maybe some further differentiation in energy systems for other countries. This could again lead to applying a kind of DTA, but now on the basis of LCI data. A further problem is that LCI data cover unit processes in great detail. Scaling up from specific product LCAs to (e.g.) 59 broad product categories of imports can lead to further errors.

3. Including Unidirectional Trade. A practitioner may identify the main trading partners of a country, make available EE I−O tables for these countries or country groups, and calculate the embedded pollution and resource use in bilateral trade with these specific countries.[7,11,12,20,21] For the exporting countries, the DTA is applied in order to include estimates of impacts associated with the imports going into the production process of the exporting country. This method, hence, discerns various trading partners, while the EU27 SUT/IOT only gives an aggregated import vector that, hence, needs to be split up by country of origin. Usually, auxiliary trade data (e.g., from COMEXT or UN COMTRADE) are used to calculate import shares to split up the import vector by country of origin. This method considers only trade between one focal country and its (main) trading partners, without representing trade among the trading partners. This, in essence, implies that it is assumed that an imported product is made in full in the country that exports it.

4. Multiregional EE IO Approach. More comprehensively, a practitioner could apply a truly multiregional approach. Here, economies of the rest of the world are presented together with the country of interest in a multiregional input−output table with environmental extensions (MR EE IO). Compiling MR EE IO databases demands a high level of harmonization and consolidation of different data sources which often conflict (e.g., trade statistics usually differ from trade data in SUIOT). Usually the research community does such harmonization,[23] by necessity changing the originally sourced statistics in the process. MR IO databases include (expansions of) GTAP,[24−28] GRAM, and others based on OECD IOTs,[5,17,29,30] and the more recent EXIOBASE,[9,31] WIOD,[32] and EORA databases.[33,34] The main difference with the unidirectional trade approach is that impacts embodied in trade *between* the non-EU regions are also estimated. This gives additional reliability compared to the unidirectional trade model.[35] The difference in results from full MRIO and unidirectional trade models is limited when national carbon footprints are calculated, being some 1−4%, but the difference becomes larger when carbon footprints of specific product groups are analyzed.[14,36,37]

5. Emissions Embodied in Bilateral Trade (EEBT).[38,39] Territorial impacts are split between domestic consumption and exports. Emissions embodied in imports of an importing country are simply the sum of territorial emissions of all exporting countries embodied in the exports to the importing country. As such, the supply chains of a product are cut off—the impacts embodied in imports are not included in the impacts embodied in exported goods. This approach avoids the double counting of impacts embodied in trade when analyzing trade flows [38] (for example, emissions associated with coal mining in Australia are embodied in the import of coal to China; the burning of coal in steel production is embodied in exports of steel from China; but the emissions occurring in Australia are not embodied in the export of steel from China, despite being upstream in the process chain, to avoid counting it twice in the trade flows). The approach only uses the domestic technology matrix and bilateral trade flows for each country. Unlike the other methods, the EEBT method is not

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applicable in the life-cycle or footprint context, as country boundaries (arbitrarily) cut off the life-cycle processes.

From the point of view of statistical offices, all these approaches have significant drawbacks. As discussed, the DTA leads usually to erroneous results. The other four approaches rely on data sets that are not gathered and validated by formal Statistical Institutes, or rely on (significant) adaptation of statistical data of other countries and other estimates. Examples are emission data for non-EU countries (usually not available by industry sector), the countries of origin of imports (not given in the European SUIOT), imbalances in trade data (imports from country X reported by country Y do not equal the reported exports by country X to country Y), etc. This makes it difficult for statistical bodies such as Eurostat to apply the methods above.

3. ALTERNATIVE USING STATISTICAL DATA ONLY: PRICE CORRECTED DOMESTIC TECHNOLOGY ASSUMPTION

We, hence, developed an approach that would use official statistical data only while still providing a meaningful correction of the DTA. We tested it for the EU27. We first considered there can be three main reasons why the DTA may not give correct results:

1. For the same industry and product, the direct pollution per physical unit of production abroad differs from the direct pollution in Europe (i.e., there is a difference in emission coefficients in the producing industries).
2. For the same industry and product, the intermediate inputs related to production of intermediate inputs per unit of production are different from those in Europe (i.e., there is a difference in the technical (input) coefficients in the producing industries).
3. For the same product, one Euro of imports represents a different physical amount of imports than one Euro of production in Europe (many countries abroad are able to produce more for less money). The DTA assumes that 1000 Euro worth of clothes made in Europe pollutes as much as 1000 Euro worth of clothes made abroad. It is, however, obvious that if 1000 Euro spent abroad buys 3 times as many clothes (of similar quality) as 1000 Euros spent domestically, about 3 times as much pollution abroad is likely to occur—even if the technology used abroad is equal to the European technology.

An important goal of analyses of pollution embodied in trade in the context of consumption based accounting is to support sustainable consumption policies.[40−44] Yet, we would argue that the first two points mentioned above are best solved via policies in which the country of exports improves its eco-efficiency [refs 45 and 46, paragraph 58i], possibly with the help of importing countries via, for example, the Joint Implementation and Clean Development Mechanisms.[47] To come to such insights, analysis of pollution embodied in trade is not essential—for instance, differences in emission factors can simply be analyzed by comparing traditional sector-based emission accounts. Or, stated differently, importing countries may feel it is not always justified for them to be held accountable for pollution embodied in trade that could be avoided if exporters used best available technologies. Understanding the level of pollution embodied in trade which is not related to this factor, i.e. point 3 above, is hence policy relevant information for importing countries.

This leads to a simple possibility to calculate a partially corrected DTA using only statistical data available from a single country/region, such as Eurostat. As indicated, Eurostat has available an EE SUIOT that contains an import and export vector discerning 59 product categories. Like most national statistical offices, Eurostat has also a very detailed insight in the trade flows of goods, which represent the main part of the total trade volume (services being of limited relevance, as shown later in this paper). Eurostat's COMEXT database contains data on both the economic value as well as the physical quantity of imported and exported products. COMEXT's detailed trade data can easily be aggregated to the product categories in the EE SUIOT. With both economic value and physical quantity known, the trade weighted average value per physical unit for each product group can be calculated for imports and exports. Assuming price homogeneity in the EE SUIOT, the price of the exports equals the price of domestic production. The ratio of domestic (=export) price and import price can then be used to adjust impacts per imported product group calculated via the DTA. This factor corrects, in essence, for each product category how much more physical imports take place per Euro spent compared to physical output per Euro production in Europe.

Since we focus on a large economy such as the EU27 and use a rather aggregated SUT, which divides the economy into 59 product categories, we assume that per category the product mix in imports is the same as for domestic production. This full substitutability of imports and domestic production is a standard assumption made in Computable General Equilibrium (CGE) models using such SUT/IOTs as core.

4. MATERIALS AND METHODS

EE SUIOT. EE SUT for the EU27 from 2000 to 2006 were sourced from Eurostat.[1,2] They contain 59 industry sectors and 59 product groups, and 8 emissions per industry (CO_2, CH_4, NH_3, SO_x, NMVOC, N_2O, SF_6, HFCs, and PCFs). The time series are available in current prices (the resulting time series of emissions is in tonnes and, hence, not affected by inflation). The supply use table was transformed into a product by product IOT using the industry technology assumption described as model B in the Eurostat manual.[48] A product by product IOT (rather than an industry by industry IOT) was essential, since the price information we use in the price-corrected DTA is only available for product groups, not for outputs of industries. Following the Eurostat manual's recommendation, the supply use tables available contain a use table that has a separate domestic use table and import use table which can be converted into separate domestic and import input−output tables. Also, final demand is available as a separate final demand for domestic and imported products.

COMEXT Data. The import and export data from COMEXT for 2000 to 2006 were provided by Eurostat. They were aggregated by Eurostat from the original 10,000 products discerned in COMEXT to the 59 product groups discerned in the SUT, using an allocation matrix available at Eurostat. Economic values from COMEXT are in current prices, as per the SUT, but pricing becomes irrelevant, as values for the same product categories are only used to calculate a ratio of adjustment.

Population Data. Environmental impacts of consumption often are expressed in impacts per capita. Population data for the EU27 between 2000 and 2006 were sourced from Eurostat.[49]

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Price Calculation. For 30 out of the 59 product groups in the EU27 SUT, both monetary and physical values were available, allowing calculation of a price for imported and exported products (see Table 2). For 23 product groups, mainly services, only monetary values were available (see Table S1, Supporting Information). For 6 other product groups, trade data were not complete enough. It concerned, e.g. uranium and thorium ores, machinery not elsewhere classified, and electrical energy, gas, steam, and hot water (see Table S2 of the Supporting Information). This resulted in unrealistic year to year import or export price variations; we rejected products where the import or export prices per year resulted in a standard deviation larger than 50%. For these remaining 29 product groups, we assumed an import price/export price ratio of 1. They represent just around 20% of the EU imports in terms of value (see Table S3 of the Supporting Information).

CIF/FOB Correction. A complication when trying to compare the price of imported and exported products is that imports and exports are reported in different prices. Imported products include transport and insurance margins ("Cost, Insurance, Freight" or CIF), while exports are reported excluding this ("Free on board" or FOB). Therefore, a CIF/FOB price level adjustment was made on the imports. To be able to do so, CIF/FOB ratios had to be estimated for the imports for each product group. Ideally, these CIF/FOB ratios would be calculated as a weighted average of the external trade CIF/FOB ratios of the individual countries and product groups. However, these ideal data were not available, and we had to resort to a much more simplified method that did not take into account (1) that CIF/FOB ratios of intra- and extra-EU trade are likely different because of the different transport modes and distances, and (2) that the CIF/FOB ratios of the different product groups are different. Country specific generic CIF/FOB ratios were available for 12 countries;[50] see Table 1. For Ireland, the CIF/FOB ratio referred to extra EU trade. For all other countries, the generic CIF/FOB ratio applied to all imported products. These CIF/FOB ratios were then used to make a weighted average CIF/FOB ratio for the EU27. It should be noted that the differences in CIF and FOB prices is between 2.5 and 10%, implying a limited influence of mistakes in this correction.

Table 1. CIF/FOB Ratios for the Twelve Countries Where a Generic CIF/FOB Ratio Is Available[a50]

code	country	CIF/FOB ratio (%)
BG	Bulgaria	8
CY	Cyprus	10
DK	Denmark	3.7
EE	Estonia	5
ES	Spain	4.5
HU	Hungary	2.66
IE	Ireland	4.8
LT	Lithuania	5.6
PL	Poland	2.5
PT	Portugal	4.67
RO	Romania	7.7
SI	Slovenia	3.93

[a]Taken from OECD.

Calculation of the Price Correction. The price correction on the emissions associated with imported products and subsequent analysis of the emissions associated with consumption in the European Union was carried out according to the following logic.

The usual way of applying the domestic technology assumption is by summing up the direct domestic requirements and direct import requirements matrix (e.g., refs [37] and [51]):

$$\mathbf{A}^d + \mathbf{A}^m = \mathbf{A}^{tot} \quad (1)$$

where $\mathbf{A}^d$ is the domestic input−output coefficient matrix (direct domestic requirements), $\mathbf{A}^m$ is the import input−output coefficient matrix (direct import requirements), and $\mathbf{A}^{tot}$ is the total input−output coefficient matrix (direct total requirements). Similarly, the final demand for domestic products and imported products can be summed to obtain the total final demand for products:

$$\mathbf{y}^d + \mathbf{y}^m = \mathbf{y}^{tot} \quad (2)$$

The direct and indirect emissions associated with total final demand and applying the DTA can be calculated using the familiar Leontief inverse:

$$\mathbf{m} = \mathbf{R}(\mathbf{I} - \mathbf{A}^{tot})^{-1}\mathbf{y}^{tot} \quad (3)$$

where $\mathbf{R}$ is the direct environmental interventions matrix and $\mathbf{m}$ is the column vector of direct plus indirect environmental interventions associated with total final consumption $\mathbf{y}^{tot}$. A formal derivation of the DTA assumption from a full two region model can be found, among others, in ref 51. The previous equation can be rewritten in such a way that the domestic technology assumption is made explicit by replacing $\mathbf{A}^{tot}$ and $\mathbf{y}^{tot}$ by their domestic and import parts:

$$\mathbf{m} = \mathbf{R}(\mathbf{I} - (\mathbf{A}^d + \mathbf{A}^m))^{-1}\mathbf{y}^d + \mathbf{R}(\mathbf{I} - (\mathbf{A}^d + \mathbf{A}^m))^{-1}\mathbf{y}^m \quad (4)$$

Note, the domestic technology assumption uses two components as explained above to represent overseas technology: (1) the emission intensities $\mathbf{R}$ are assumed the same in the production of goods that were imported to those produced domestically; (2) the production functions/recipes (denoted by $\mathbf{A}^d + \mathbf{A}^m$) are the same for the domestic economy as the overseas economy.

$\mathbf{A}^d$ and $\mathbf{A}^m$ are expressed as a ratio in current year market exchange rate prices (e.g., €/€). However, the unit value (price) of domestically produced products might differ from the price of imported products, as we observe in the trade data of COMEXT. Assuming that inputs to (or emissions from) production are more closely related to the quantity of the goods, rather than the value of the goods, a price correction on the imported products would reflect the emissions associated with imported products better than with the simple DTA. Hence, we correct our consumption variables for imported goods $\mathbf{A}^m$ and $\mathbf{y}^m$ with the price correction vector $\mathbf{c}$ showing price of imported goods $\mathbf{p}^m$ relative to price of domestic goods $\mathbf{p}^d$:

$$\mathbf{c} = (\hat{\mathbf{p}}^d)^{-1}\mathbf{p}^m \quad (5)$$

The price corrected import use matrix ($\mathbf{A}^{m*}$) and final demand for imported products ($\mathbf{y}^{m*}$) become the following:

$$\mathbf{A}^{m*} = \hat{\mathbf{c}}^{-1}\mathbf{A}^m \quad (6)$$

$$\mathbf{y}^{m*} = \hat{\mathbf{c}}^{-1}\mathbf{y}^m \quad (7)$$

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Table 2. Import Price/Export Price Ratios for the EU27 Calculated with COMEXT for 30 Product Groups

code	products (CPA)	year 2000	2001	2002	2003	2004	2005	2006
01	products of agriculture, hunting, and ...	1.68	1.22	1.10	1.29	0.97	1.31	1.29
02	products of forestry, logging, and ...	0.86	0.93	0.99	1.02	0.97	0.94	0.79
05	fish and other fishing products; ...	0.92	0.83	0.94	0.65	0.68	0.70	0.84
10	coal and lignite; peat	0.80	0.96	0.84	0.85	0.63	0.78	0.72
11	crude petroleum and natural gas ...	0.90	0.92	0.89	0.94	0.89	0.90	0.86
13	metal ores	0.69	0.67	0.74	0.73	0.74	0.64	0.48
14	other mining and quarrying products	0.39	0.40	0.36	0.33	0.33	0.33	0.36
15	food products and beverages	0.53	0.51	0.46	0.47	0.46	0.51	0.51
16	tobacco products	0.29	0.30	0.28	0.33	0.36	0.42	0.43
17	textiles	0.66	0.66	0.61	0.59	0.68	0.70	0.77
18	wearing apparel; furs	0.90	0.45	0.77	0.74	0.87	0.87	0.80
19	leather and leather products	0.38	0.30	0.34	0.32	0.31	0.32	0.33
20	wood and products of wood and ...	1.06	1.07	1.03	0.97	0.97	1.00	1.00
21	pulp, paper, and paper products	0.82	0.81	0.78	0.82	0.85	0.86	0.89
22	printed matter and recorded media	0.96	1.09	1.05	0.94	0.48	0.76	0.79
23	coke, refined petroleum products ...	0.81	0.81	0.76	0.77	0.78	0.81	0.82
24	chemicals, chemical products, and ...	0.49	0.50	0.48	0.50	0.54	0.58	0.55
25	rubber and plastic products	0.93	0.90	0.88	0.82	0.85	0.87	0.88
26	other nonmetallic mineral products	0.76	0.73	0.58	0.59	0.59	0.62	0.57
27	basic metals	1.38	1.22	1.37	1.40	1.22	1.03	0.98
28	fabricated metal products, except ...	0.89	0.66	0.81	0.69	0.65	0.67	0.71
30	office machinery and computers	0.61	0.55	0.61	0.80	0.34	0.43	0.51
31	electrical machinery and apparatus ...	1.15	1.12	0.96	0.86	0.99	0.92	0.94
32	radio, television, and comm ...	1.25	1.13	1.14	1.16	0.43	0.31	0.57
33	medical, precision, and optical ...	0.99	0.60	0.86	0.80	0.68	0.60	0.68
34	motor vehicles, trailers, and semi-...	0.90	0.95	0.93	0.90	1.00	1.02	1.05
35	other transport equipment	1.11	1.01	2.27	0.58	0.52	0.31	0.30
36	furniture; other manufactured ...	0.73	0.69	0.71	0.61	0.58	0.59	0.58
72	computer and related services	0.76	0.71	1.10	0.55	0.52	0.62	0.83

The price corrected environmental interventions associated with the final consumption of products then becomes the following:

$$\mathbf{m}^* = \mathbf{R}(\mathbf{I} - (\mathbf{A}^d + \mathbf{A}^{m^*}))^{-1}\mathbf{y}^d + \mathbf{R}(\mathbf{I} - (\mathbf{A}^d + \mathbf{A}^{m^*}))^{-1}\mathbf{y}^{m^*} \quad (8)$$

The second right-hand term $(\mathbf{I} - (\mathbf{A}^d + \mathbf{A}^{m*}))^{-1}\mathbf{y}^{m*}$ describes the production of products in non-EU countries which will be imported into the EU. It is still assumed that the non-EU production technology is the same as the EU27 production technology, and hence, eq 8 describes a DTA method but with a price correction. As a side note, the column sums of $\mathbf{A}^{tot}$ change under the price correction (possibly even going larger than 1). This is due to the different valuations of the imports (now expressed in € according to purchasing power, rather than € according to market exchange rates, per € output) and is synonymous to the issue of nonadditive rows in mixed-unit input–output analysis.[52]

5. RESULTS

Import/Export Price Ratios. Table 2 shows the results of price ratios for the 30 product groups for which economic and physical data were available, after CIF/FOB correction. Some of the product groups are on average produced more inexpensively in the EU27 than outside the EU27, notably agriculture products, wood products, and basic metals. Some product groups were produced more inexpensively in 2000 in the EU but were more expensively produced in the EU in 2006. It seems to be the overall trend that the price of products produced in the EU becomes more expensive compared to the price of products outside the EU and imported into the EU. The average price ratio of imports falls from 0.84 in 2000 to 0.68 in 2006.

Price Corrected DTA Values. Figure 3 shows the consumption based CO_2 emissions for the EU27 per capita:

(a) at European territory;
(b) in imports to Europe
(c) in exports from Europe
(d) related to European domestic final consumption.

Emissions embodied in imports to Europe are given both via the traditional DTA method and via the price adjusted DTA. Part of these emissions embodied in imports end up in emissions embodied in exports as well as in emissions embodied in final domestic consumption. Emissions of EU27 final domestic consumption correspond to emissions at EU27 territory plus emissions in imports minus emissions in exports.

The figures show that when the DTA is used, there is hardly a difference between emissions embodied in imports and those embodied in exports in all years between 2000 and 2006. Indeed, in 2000 the emissions embodied in imports calculated with the DTA are even slightly lower than those embodied in exports. Domestic emissions, hence, are almost the same as emissions related to final demand. The price adjusted DTA shows a significant difference. Compared to the regular DTA, much higher values are calculated for CO_2 emissions embodied in imports: 0.4 t/cap in 2000 and 1 t/cap in 2006. Of this additional CO_2 embodied in imports, just a small part ends up

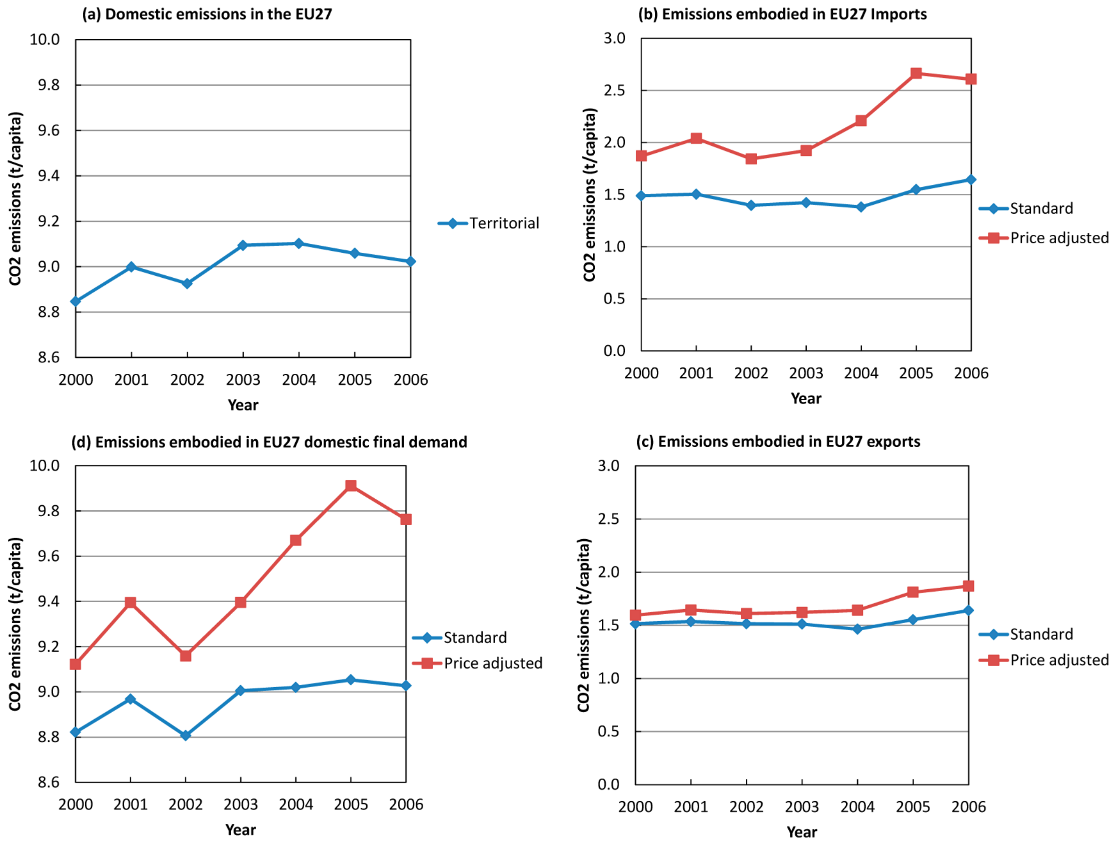

Figure 3. CO_2 emissions per capita, 2000–2006: (a) emitted at EU27 territory; (b) embodied in EU27 imports; (c) embodied in EU27 exports; and (d) embodied in EU27 domestic final demand, calculated with Domestic Technology Assumption ("standard") and with price adjustments.

in exports. As a result, the CO_2 emissions of EU27 domestic final consumption rise by the use of the price-adjusted DTA by around 0.3 t/cap in 2000 to 0.8 t/cap in 2006 compared to calculations with the regular DTA. These numbers are significant. It leads to consumption-based emissions which are for 2006 almost 10% higher than territorial emissions.

Figure S1 in the Supporting Information gives the total CO_2 emissions of the EU27. It reflects the same pattern as Figure 3, since the change in population in the EU27 was limited between 2000 and 2006.

As indicated, the price-adjusted DTA does not give full insight into pollution embodied in imports. (MR) EE IO studies, in theory, could provide a benchmark to analyze what fraction of pollution embodied in European trade our adjustment covers. Yet, this field has not yet sufficiently matured. For instance, Davis and Caldeira[18] found uncertainties in the GTAP database they used for their work "impossible to quantify". This paper is not the place for an in-depth comparison between the few MR EE IO studies published thus far, but the summary in Table 3 shows quite deviating results. Due to the use of different data sets for SUT/IOT and emissions, and different construction approaches (e.g., refs 53–55), studies give different numbers for the per capita CO_2 emissions in net imports, the CO_2 emissions of final consumption, and the territorial CO_2 emissions for the EU27. It is particularly striking that even the domestic/territorial CO_2 emissions estimated for the EU27 differ almost 10% for the same year across studies, up to 0.8 t/cap in 2004 between Peters et al.[27] and Davis and Caldeira.[18] This is the same order of magnitude of the difference between emissions in final demand and domestic emissions within studies (e.g., 1.9 t/cap in 2004[18] and 1.8 t/cap in 2004[27]).

Table 3. CO_2 Emissions per Capita for the EU27 from Different Perspectives, as Reported by Different Authors[a]

parameter	year	value	author
domestic emissions EU27	2000	9.6 t/cap	Tukker et al.[31]
	2000	8.85 t/cap	Eurostat,[2] this study
	2004	8.6 t/cap	Davis and Caldeira[18]
	2004	9.4 t/cap	Peters et al.[27]
	2004	9.1 t/cap	Eurostat,[2] this study
	2006	9.13 t/cap	Peters et al.[27]
	2006	9.02 t/cap	Eurostat,[2] this study
emissions in domestic final demand EU27	2000	10.1 t/cap	Tukker et al.[31]
	2004	10.5 t/cap	Davis and Caldeira[18]
	2004	10.2 t/cap	Peters et al.[27]
	2006	10.3 t/cap	Peters et al.[27]
emissions in imports–exports of EU27	2000	>2 t/cap	Brückner et al.[17]
	2000	0.5 t/cap	Tukker et al.[31]

[a]Absolute values were where needed recalculated to values per capita with EU27 population numbers from Eurostat [49].

6. REFLECTION AND DISCUSSION

This paper presents a relatively simple and partial adjustment of the DTA that can be calculated with statistical data available at statistical offices rather than using unofficial data such as LCI databases or reconstructed statistical data, as used in MR IO databases. We propose to use the DTA, corrected for the price differences in imports and domestic production using monetary and physical data present in official import and export statistics. This gives insight into the pollution embodied in trade that would occur if the exporting countries applied production technologies that are equally efficient and clean, as in the country of imports.

Our case study for the EU27 shows that, using the DTA only, there is hardly a difference between CO_2 emissions in imports and exports of the EU27. This is in stark contrast with results calculated with MR EE IO databases, that typically find that carbon emissions in EU27 imports can be up to 3 ton per capita higher than in exports.[17,18,27,31] Our price adjusted DTA suggests a net CO_2 emission embodied in trade (imports−exports) of 0.3 ton/cap in 2000 and 0.8 ton/cap in 2006. This results in carbon footprints of domestic consumption which are almost 10% higher than the territorial emissions (9.8 versus 9.0 t/cap) for the EU27 in 2006.

Ideally, we would like to analyze what fraction of pollution embodied in EU27 imports is covered by the price-adjusted DTA. If there would be a well validated MR EE IO database available, ideally one that includes physical data on sector production volumes and trade, we could have analyzed via contribution analyses which factor contributes mostly to pollution embodied in EU27 imports: emission intensities abroad, inefficiencies in production abroad, or the differences in price per physical volume produced between other countries and Europe captured by our price adjusted DTA. Table 3, however, shows that current MR EE IO databases have significant and unknown uncertainties. Even simple numbers such as EU27 territorial CO_2 emissions, differ almost 10% or 0.8 t/cap for 2004 between studies. The difference between territorial emissions and emissions attributed to final demand varies between less than 0.6 t/cap (ref 31) and >2 t/cap (ref 17) for 2000, 1.9 t/cap (ref 18) or 1.1 t/cap (ref 27) for 2004, and 1.2 t/cap (ref 27) in 2006. Our price adjusted DTA results in a difference of 0.3 t/cap in 2000 and 0.8 t/cap in 2006. This is lower than that found in MR EE IO studies, which is in line with the fact that the price corrected DTA is only a partial correction for measuring pollution embodied in imports. It is also clear that the price adjusted DTA covers a significant amount of the net pollution embodied in trade found by MR EE IO studies. Finally, the trend that CO_2 embodied in imports rises between 2000 and 2006 is in line with the findings of Davis and Caldeira,[18] Brückner et al.[17] and Peters et al.[27] Without a more solid benchmark, we feel we must refrain from statements such as for our case study the price adjusted DTA corrects just 20% or close to 50% of the difference of pollution embodied in trade calculated with the regular DTA and a full MR EE IO approach.

Particularly since the method uses statistically validated data only, we think it is a promising method for statistical offices to report pollution embodied in imports without being dependent on external data. Of course the price corrected DTA still contains some drawbacks of the original DTA, such as that for certain product categories the imported product mix may differ from the domestically produced product mix. This can be assumed relatively unimportant in our case, covering a large economic block such as the EU, but particularly for smaller countries, this problem can be problematic.[10] Further, it must be reiterated that the method only gives partial insight into pollution embodied in trade; depending on the goal of the study, it could additionally be considered to apply a simple CO_2 emissions/unit economic output adjustment factor rather than to completely ignore technological differences between importing and exporting countries.

■ ASSOCIATED CONTENT

Supporting Information

A numerical example of the transformation of SUT to IOT and the calculation of the traditional and price adjusted DTA, next to the list of 29 services responsible for 20% of EU imports for which no price correction could be made, and an additional figure showing results in absolute CO_2 emissions for the EU27. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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■ REFERENCES

(1) *Manual for Air Emissions Accounts*; Eurostat: Luxembourg, 2009.

(2) *Creating aggregated EU27 Input-Output Tables, adding environmental extensions (air emissions), and conducting Leontief-type modelling to approximate carbon and other 'footprints' of EU27 consumption*; Eurostat: Luxembourg, 2011.

(3) Ten Raa, T. *The Economics of Input-Output Analysis*; Cambridge University Press: Cambridge, U.K., 2005.

(4) Miller, R. E., Blair, P. D. *Input-output analysis: Foundations and extensions*; Cambridge University Press: Cambridge, U.K., 2009.

(5) Giljum, S.; Behrens, A.; Hinterberger, F.; Lutz, C.; Meyer, B. Modelling scenarios towards a sustainable use of natural resources in Europe. *Environ. Sci. Policy* **2008**, *11* (3), 204−216.

(6) Wiedmann, T.; Wood, R.; Minx, J. C.; Lenzen, M.; Guan, D.; Harris, R. Carbon footprint time series of the UK—results from a multi-region input-output model. *Econ. Syst. Res.* **2010**, *22* (1), 43−63.

(7) Druckman, A.; Jackson, T. The carbon footprint of UK households 1990−2004: A socio-economically disaggregated, quasi-multi-regional input-output model. *Ecol. Econ.* **2009**, *68* (7), 2066−2077.

(8) Wiedmann, T.; Lenzen, M.; Turner, K.; Barrett, J. Examining the global environmental impact of regional consumption activities—part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. *Ecol. Econ.* **2007**, *61* (1), 15−26.

(9) Tukker, A.; Poliakov, E.; Heijungs, R.; Hawkins, T.; Neuwahl, F.; Rueda-Cantuche, J.; Giljum, S.; Moll, S.; Oosterhaven, J.; Bouwmeester, M. Towards a global multi-regional environmentally extended input-output database. *Ecol. Econ.* **2009**, *68* (7), 1929−1937.

(10) Peters, G. P.; Hertwich, E. G. The Importance of Imports for Household Environmental Impacts. *J. Ind. Ecol.* **2006**, *10* (3), 89−109.

(11) Wood, R.; Dey, C. J. Australia's carbon footprint. *Econ. Syst. Res.* **2009**, *21* (3), 243−266.

(12) Weber, C. L.; Matthews, H. S. Embodied environmental emissions in U.S. international trade, 1997−2004. *Environ. Sci. Technol.* **2007**, *41* (14), 4875−4881.

(13) Ghertner, D. A.; Fripp, M. Trading away damage: Quantifying environmental leakage through consumption-based, life-cycle analysis. *Ecol. Econ.* **2007**, *63* (2−3), 563−577.

(14) Andrew, R.; Peters, G. P.; Lennox, J. Approximation and regional aggregation in multi-regional input-output analysis for national carbon footprint accounting. *Econ. Syst. Res.* **2009**, *21*, 311−335.

(15) Minx, J. C.; Wiedmann, T.; Wood, R.; Peters, G. P.; Lenzen, M.; Owen, A.; Scott, K.; Barrett, J.; Hubacek, K.; Baiocchi, G.; Paul, A.; Dawkins, E.; Briggs, E.; Guan, D.; Suh, S.; Ackerman, F. Input Output analysis and carbon footprinting: an overview of applications. *Econ. Syst. Res.* **2009**, *21* (3), 187−216.

(16) Su, B.; Ang, B. W. Input−output analysis of CO_2 emissions embodied in trade: the effects of spatial aggregation. *Ecol. Econ.* **2010**, *70* (1), 10−18.

(17) Brückner, M.; Polzin, C.; Giljum, S. *Counting CO_2 emissions in a Globalised World*; Discussion Paper 9/2010; Deutsches Institut für Entwicklungspolitik: Bonn, Germany, 2010.

(18) Davis, S.; Caldeira, K. Consumption-based accounting of CO_2 emissions. *Proc. Natl. Acad. Sci. U.S.A.* **2010**, Vol. *107* (12), 5687−5892

(19) *RME estimations & coefficients—explanatory notes*; Eurostat; Luxembourg, 2012.

(20) Weidema, B. P.; Suh., S.; Notten, P. Setting priorities within product oriented environmental policy: The Danish perspectives. *J. Ind. Ecol.* **2006**, *10* (3), 73−87.

(21) Nijdam, D. S.; Wilting, H. C.; Goedkoop, M. J.; Madsen, J. Environmental Load from Dutch. Private Consumption. *J. Ind. Ecol.* **2005**, *9* (1−2), 147−168.

(22) *Statistics in focus 22/2011*; Eurostat: Luxembourg, 2011.

(23) Wiedmann, T. A review of recent multi-region input-output models used for consumption-based emission and resource accounting. *Ecol. Econ.* **2009**, *69* (2), 211−222.

(24) Narayanan, B., Aguiar, A., McDougall, R., Eds. *Global Trade, Assistance, and Production: The GTAP 8 Data Base*; Center for Global Trade Analysis, Purdue University: West Lafayette, IN, 2012.

(25) Hertwich, E. G.; Peters, G. Carbon footprint of nations: a global, trade-linked analysis. *Environ. Sci. Technol.* **2009**, *43*, 6414−6420.

(26) Peters, G. P.; Andrew, R.; Lennox, J. Constructing an environmentally extended multi-regional input-output table using the GTAP database. *Econ. Syst. Res.* **2011**, *23* (2), 131−152.

(27) Peters, G. P.; Minx, J. C.; Weber, C. L.; Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. U.S.A.* **2011**, *108* (21), 8903−8908.

(28) Chen, Z. M.; Chen, G. Q. An overview of energy consumption of the globalized world economy. *Energy Policy* **2011**, *39* (10), 5920−5928.

(29) Brückner, M.; Giljum, S.; Lutz, C.; Wiebe, K. S. Materials embodied in international trade—Global material extraction and consumption between 1995 and 2005. *Global Environ. Change* **2012**, *22* (3), 568−576.

(30) Chen, Z. M.; Chen, G. Q. Greenhouse gas emissions and natural resources use by the world economy: Ecological input−output modeling. *Ecol. Modell.* **2011**, *222*, 2362−2376.

(31) Tukker, A.; de Koning, A.; Wood, R.; Hawkins, T.; Lutter, S.; Acosta, J.; Rueda Cantuche, J. M.; Bouwmeester, M. C.; Oosterhaven, J.; Drosdowski, T.; Kuenen, J. EXIOPOL—Development and Illustrative Analyses of a Detailed Global MR EE SUT/IOT. *Econ. Syst. Res.* **2013**, *25* (1), DOI: http://dx.doi.org/10.1080/09535314.2012.761953.

(32) Dietzenbacher, L. B.; Stehrer, R.; Timmer, M.; de Vries, G. The Construction of World Input-Output Tables in the WIOD Project. *Econ. Syst. Res.* **2013**, *25* (1), DOI: http://dx.doi.org/10.180/09535314.2012.761180.

(33) Lenzen, M.; Kanemoto, K.; Moran, D.; Geschke, A. Mapping the Structure of the World Economy. *Environ. Sci. Technol.* **2012**, *46* (15), 8374−81.

(34) Lenzen, M.; Moran, D.; Kanemoto, K.; Foran, B.; Lobefaro, L.; Geschke, A. International trade drives biodiversity threats in developing nations. *Nature* **2012**, *486*, 109−112.

(35) Su, B.; Ang, B. W. Multi-region input-output analysis of CO_2 emissions embodied in trade: The feedback effects. *Ecol. Econ.* **2011**, *71* (1), 42−53.

(36) Wilting, H. C. Sensitivity and uncertainty analysis in MRIO modelling, some empirical results with regard to the Dutch Carbon footprint. *Econ. Syst. Res.* **2012**, *24:2*, 141−171.

(37) Lenzen, M.; Pade, L.-L.; Munksgaard, J. CO_2 Multipiers in Multi-region Input−Output Models. *Econ. Syst. Res.* **2004**, *16*, 391−412.

(38) Peters, G. P. From production-based to consumption-based national emissions inventories. *Ecol. Econ.* **2008**, *65* (1), 13−23.

(39) Gavrilova, O.; Vilu, R. Production-based and consumption-based national greenhouse gas inventories: An implication for Estonia. *Ecol. Econ.* **2012**, *75*, 161−173.

(40) Fuchs, D.; Lorek, S. Sustainable consumption governance: A history of promises and failures. *J. Consum. Policy* **2005**, *28* (3), 261−288.

(41) Hertwich, E. G. Life cycle approaches to sustainable consumption: A critical review. *Environ. Sci. Technol.* **2005**, *39* (13), 4673−4684.

(42) Tukker, A.; Cohen, M. J.; de Zoysa, U.; Hertwich, E. G.; Hofstetter, P.; Inaba, A.; Lorek, S.; Stø, E. The Oslo declaration on sustainable consumption. *J. Ind. Ecol.* **2006**, *10*, 9−14.

(43) Tukker, A.; Cohen, M. J.; Hubacek, K.; Mont, O. The Impacts of Household Consumption and Options for Change. *J. Ind. Ecol.* **2010**, *14* (1), p13−30.

(44) *Letter dated 18 June 2012 from the Permanent Representative of Brazil to the United Nations addressed to the Secretary-General of the United Nations Conference on Sustainable Development. A 10-year framework of programmes on sustainable consumption and production patterns*. Rio+20 United Nations Conference on Sustainable Development, Rio de Janeiro, Brazil, A/CONF.216/5*. Available from: http://www.unep.org/rio20/portals/24180/Docs/a-conf.216-5_english.pdf.

(45) Tukker, A. Leapfrogging into the future. *Int. J. Innovation Sustainable Dev.* **2005**, *1* (1−2), 65−84.

(46) *The future we want*. UN: New York/Rio de Janeiro, 2012; available from: http://www.un.org/en/sustainablefuture/, accessed 26 July 2012.

(47) Annex, I. In *Climate Change 2007*; Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, U.K., 2007.

(48) *Eurostat Manual of Supply, Use and Input-Output Tables*; Eurostat: Luxembourg, 2008.

(49) *Demographic balance and crude rates. Population on 1 January—total*. Update 25 July 2012. Available from: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=demo_gind&lang=en, accessed 26 July 2012.

(50) *Reconciling merchandise trade data and balance of payments trade in goods, 6th OECD international trade statistics expert meeting (ITS) & OECD-Eurostat meeting of experts in trade-in-services statistics (TIS) Tour Europe, Salle des Nations, 12−15 September 2005*; OECD Report No. STD/NAES/TASS/ITS(2005)10, OECD, Paris, France, 2005.

(51) Serrano, M.; Dietzenbacher, E. *Responsibility and trade emission balances: An evaluation of approaches*. *Ecological Economics* **2010**, *69*, 2224−2232.

(52) Hawkins, T.; Hendrickson, C.; Higgins, C.; Matthews, H. S.; Suh., S. *A mixed-unit input-output model for environmental life-cycle assessment and material flow analysis*. *Environ. Sci. Technol.* **2007**, *41* (3), 1024−1031.

(53) Pulles, T.; van het Bolscher, M.; Brand R.; Visschedijk, A. Assessment of Global Emissions from Fuel Combustion in the Final Decades of the 20th Century. Application of the Emission Inventory Model TEAM. *TNO Built Environment and Geosciences*; TNO Report 2007-A-R0132/B; Apeldoorn, Netherlands, 2007.

(54) Peters, G. P.; Davis, S. J.; Andrew, R. M. A Synthesis of Carbon in International Trade. *Biogeosciences* **2012**, *9*, 3247−3276.
(55) Tukker, A.; Dietzenbacher, E. Global multiregional input-output frameworks: an introduction and outlook. *Econ. Syst. Res.* **2013**, *25* (1), DOI: http://dx.doi.org/10.1080/09535314.2012.761179.