Beyond production and consumption: using throughflows to untangle the virtual trade of externalities

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Abstract

Understanding how countries contribute to the generation of externalities globally is important for designing sustainable policies aimed at reducing negative externalities such as carbon emissions. Commonly used approaches focus on either producers or consumers, thereby neglecting the role of intermediates. We here introduce the concept of *throughflow* to comprehensively quantify upstream externalities generated by the supply chains originating from, passing through or ending in a given country. We define the Throughflow Based Accounting (TBA) framework as the decomposition of the throughflow into local, imported, exported and traversing externalities. We illustrate the strength of the TBA by identifying the CO_2 emissions caused by supply chains involving the German economy. We show that Germany could use its position in global value chains to help reduce two times more CO_2 emissions than measured with usual production- or consumption-based accounting frameworks.

Introduction

Major challenges of our modern civilisation require a better control of externalities caused by human activities. Limiting global warming to well below 2°C compared to preindustrial levels as agreed upon in the Paris Agreement (*Conference of the Parties, Adoption of the Paris Agreement*, 2015) is only possible if greenhouse gas emissions reach net zero early in the second half of the 21st century (Riahi et al., 2022). Similarly, the achievement of the United Nations' Sustainable Development Goals (*Transforming Our World : The 2030 Agenda for Sustainable Development*, 2015) requires minimizing negative externalities such as local air pollution and increasing positive externalities such as employment or education.

Our current globalized economy is characterized by long, complex and often international production processes (Hummels, et al. 2001; Costinot et al. 2013; Maluck and Donner 2015; Xiao et al. 2020). Before being used at their final destination, commodities usually undergo numerous transformation steps, which involve different industries routinely located in different countries. This complexity blurs contributions to the joint production effort and therefore dilutes responsibilities for the generation of externalities (Davis et al., 2011; Peters et al., 2012; Kagawa et al., 2015; Wiedmann & Lenzen, 2018).

In addition to the economic actor directly generating externalities[1], actors involved in the supply chain associated with these externalities could also act to reduce or enhance their generation. For instance, the information that a product is causing environmental degradations may deter consumers from buying it (Rondoni & Grasso, 2021), stakeholders are increasingly considering sustainability criteria in decision making (Chatzitheodorou et al. 2019; Latapí Agudelo et al. 2019) and countries may modify their trade policies to pursue climate mitigation goals (Jakob, 2021; Jakob et al., 2022).

Multi-Regional Input Output tables (MRIOT) are commonly used to identify externalities generated both directly and indirectly for supplying commodities to final consumers (Miller & Blair, 2009, pp. 446–452; Wiedmann et al., 2015; Wiedmann & Lenzen, 2018; Wood et al., 2018). *Consumption Based Accounting* (CBA) approaches quantify externalities that could be targeted by an economic actor through demand-side measures, e.g. via changes of consumption patterns (Wood et al., 2020). CBA is the basis of the concept of *consumption footprint*. By contrast, the *Production Based Accounting* (PBA) framework measures externalities directly generated by an economic actor (Peters 2008), i.e. those an actor could target through production-side measures, e.g. technological change.

Beyond consumers and producers, intermediates could also target externalities generated along the supply chains they are involved in. Structural Path Analysis (SPA) allows decomposing supply chains by layers (Lenzen, 2003; Skelton et al., 2011) and may thus permit to identify critical intermediates in international supply chains. In a seminal paper, Liang et al. (2016) have proposed the *Betweenness Based Accounting* (BBA) measure, which combines SPA with the concept of betweenness centrality, capturing the ability of a node to transmit information in a network. In the context of MRIOs, BBA captures externalities caused by the supply chains traversing a sector, i.e. how much a sector contributes to the generation of externalities by its position as an intermediate in these supply chains. The betweenness can also be computed for edges, i.e., for a given transaction in the global economic network (Hanaka et al.,

[1] We here use the term "externalities" in its broadest sense such that it can denote both, different externality types as well as varying amounts of the same externality.

2017). Using adjacency matrices and clustering techniques, Kagawa et al. (2015) have also been able to measure the upstream CO_2 emissions related to specific trade relations. This set of methods is particularly well suited for identifying critical links or sectors in the global trade network and are readily used to explore sector-specific policies to curb the production of negative externalities, for instance by decreasing the input use from the most carbon-intense industries (Liang et al., 2016; Ward et al., 2017), or by reducing the dependence on major emissions clusters (Hanaka et al. 2017; Tokito 2018; Maeno et al. 2022; Tokito et al. 2022).

Beyond sector-specific measures, policymakers can also implement economy-wide policies to reduce their contribution to the global generation of negative externalities, e.g., by uniformly pricing the creation of externalities. The most prominent example of such externality pricing is given by carbon markets, which have been implemented in different parts of the world (Stiglitz et al., 2017; World Bank, 2022). Carbon markets usually price CO_2 emissions from domestic producers only, thus relating to PBA. However, as domestic carbon markets may cause carbon leakage in trade-exposed sectors (Dechezleprêtre & Sato, 2017; Naegele & Zaklan, 2019; Jakob, 2021; Misch, 2021), policymakers are considering the implementation of Border Adjustment Mechanisms (BAM) to level the playing field between domestic and imported production by levying a price on imported commodities based on the emissions caused elsewhere (Sakai & Barrett, 2016; Jakob, 2021).

The methods previously introduced are not directly applicable to investigate how countries could address externalities production through BAMs. First, the methods referenced therebefore are usually applied at the scale of sectors, while the investigation of BAMs calls for accounting frameworks at the national scale. In particular, a formulation of the BBA at the country level is still missing. Second, these methods entail double counting, as externalities caused by supply chains looping several times through the same sector are counted multiple times (Liang et al., 2016; Tokito et al., 2022). Such double counting impedes the investigation of externality pricing, as there is no ground to levy a price more than once on a given externality.

This double counting problem is identical to the one encountered for the taxation of value added. The Trade in Value Added (TiVA) framework provides a detailed decomposition of the value added embodied in the gross exports of a country and permits the identification of double counted elements (Koopman et al., 2010, 2014; Borin & Mancini, 2019). Though the TiVA framework is largely used for Global Value Chain (GVC) analysis in economic terms, it is rarely applied to externalities accounting problems. As highlighted by Los and Timmer (2018), the TiVA framework derives from the Hypothetical Extraction Method (HEM). The HEM is a standard technique of Input Output analysis measuring a sector's or a country's interconnectedness to the global economy (Dietzenbacher et al., 1993; Miller & Blair, 2009, pp. 563–565). It is also used to develop analytical frameworks to investigate intermediate dependencies in the global economy (Dietzenbacher & Lahr, 2013; Dietzenbacher et al., 2019). In the context of externalities accounting, the HEM can be directly interpreted as the volume of upstream externalities caused by all the supply chains starting from, traversing and ending in a given sector (Hanaka et al., 2022; Tokito et al., 2022).

Tokito et al. (2022) have shown that the HEM is closely related to BBA, the only difference being the consideration of self-loops in supply chains: the HEM counts externalities only once, even when the associated supply chain loops several times through the same sector. HEM-based techniques are hence not prone to the double counting problem and are suitable to explore externality pricing policies. In a recent work, Hanaka et al. (2022) have proposed a decomposition of the HEM to account simultaneously for the production, consumption and transmission characteristics of a sector (*production-*, *consumption-* and *betweenness-oriented* scores), but these scores lack a clear link with the PBA and CBA frameworks and are only defined at the sector level.

Our paper extends the existing literature by formulating the so-called Throughflow Based Accounting (TBA) framework. We propose the term *throughflow* to designate the total volume of externalities captured by the HEM, which is the volume of upstream externalities caused by all the supply chains starting from, traversing and ending in a given country. As the concept of *footprint* has made the use of the Leontief inverse popular beyond the Input-Output community, we believe that the concept of *throughflow* and the associated TBA framework can facilitate the communication and use of HEM-based methods and results. The TBA framework is further built on the decomposition of the throughflow into four meaningful elementary components: *local, imported*, *exported* and *traversing* externalities. Being defined at the national scale and built on intuitive concepts, the TBA framework bridges the gap between the work of Hanaka et al. (2022) and the canonical PBA and CBA frameworks (fig. 1). While the TBA is coherent with the PBA and CBA frameworks, it has a broader coverage than both of these by acknowledging simultaneously for the production, consumption and intermediate contribution of a country to externalities production worldwide.

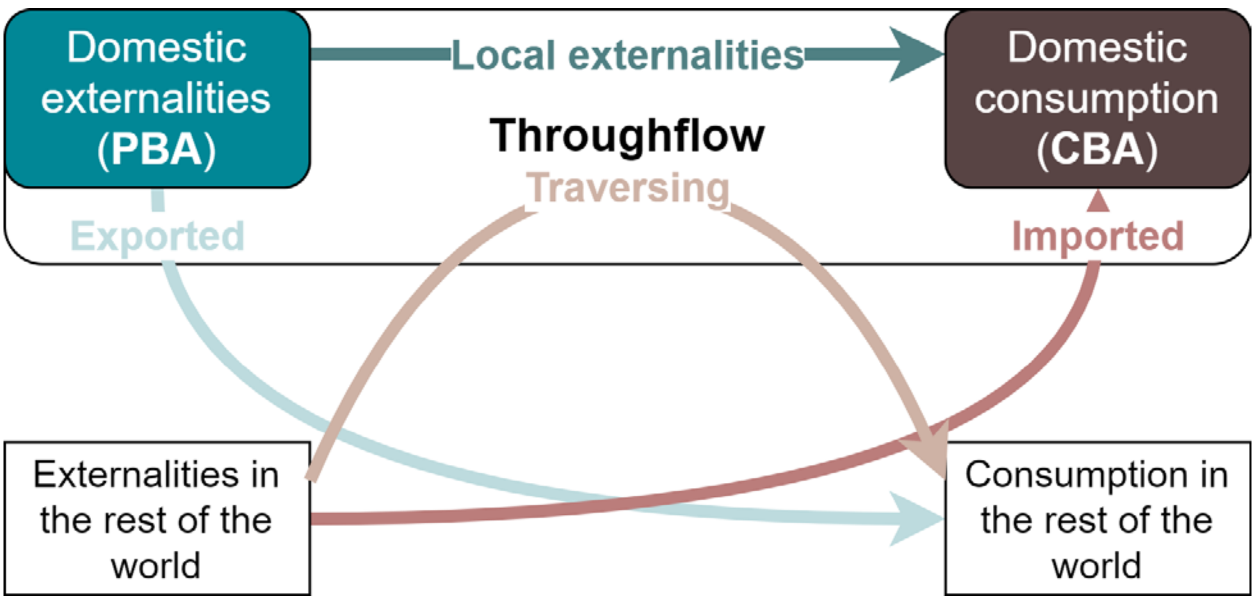

Figure 1 - Overview of the Throughflow Based Accounting (TBA) decomposition. *The throughflow quantifies the volume of upstream externalities caused by all the supply chains starting from, traversing or ending in a given country. The TBA is the decomposition of the throughflow into four elementary flows. Local and exported externalities are caused domestically to supply final users domestically and abroad, respectively. Together, they form the usual Production Based Accounting (PBA). Imported externalities are caused abroad along supply chains serving final users domestically. Local and imported externalities correspond to the Consumption Based Accounting (CBA) framework. Beyond the volumes of externalities embodied in the usual PBA and CBA frameworks, TBA also entails traversing externalities: these externalities are caused abroad to supply final consumption abroad, but the associated supply chains involve the local economy at least once in between.*

The second section of this paper introduces the formal definition of the *throughflow* and derives the TBA decomposition from it. In the third section, we illustrate how the TBA can straightforwardly be applied to identify the externalities caused along the supply chains a country is involved in. As an example, we investigate the CO_2 throughflow of the German economy. We discuss the results of the study case and their policy implications in the fourth section, in relation with pre-existing accounting frameworks. Finally, the fifth section summarizes the main findings of this paper and outlines avenues for further research.

Method description

In this section, we introduce the Throughflow Based Accounting (TBA) framework and anchor it within pre-existing frameworks. We first recap some basic relations of Input-Output Analysis (IO). Second, we introduce the concept of *throughflow* as an interpretation of the Hypothetical Extraction Method (HEM). Then, we formulate the TBA by decomposing the *throughflow* based on the position of a country in supply chains causing externalities. Finally, we compare the TBA to other accounting frameworks. As a global convention, we note matrices with capital letters and vectors with lowercases. Elements of matrices are indicated with subscripts. We here introduce the TBA at the scale of a country c, but the definitions can be extended to any group of countries or regions.

Basic definitions

A Multi Regional Input Output Table (MRIOT) describes the global production network (Miller & Blair, 2009; Lenzen et al., 2012). We note n the number of sectors and N the number countries covered. MRIOTs are characterized by the equation which puts the column vector of gross output $\mathbf{x}$ into relation with the matrix of input coefficients $\mathbf{A}$ and the matrix of final demand $\mathbf{Y}$:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}\mathbf{e} = \mathbf{L}\mathbf{Y}\mathbf{e}. \tag{1}$$

$\mathbf{A}$ is a matrix of dimensions $nN \times nN$. The input coefficient $a_{ir\to js}$ of $\mathbf{A}$ describes the quantity of output from sector i in country r that is directly used as input for the production of one unit of output by sector j in country s. This element corresponds to the $(r-1)n+i$-th row, $(s-1)n+j$-th column of the $\mathbf{A}$ matrix and is often noted a_{ir}^{js} in the literature. Unlike usual conventions, we here note both regions and sectors as subscripts in order to reserve superscripts for country specific variables. The matrix $\mathbf{L}$, defined as $(\mathbf{I}-\mathbf{A})^{-1}$ (with $\mathbf{I}$ the identity matrix) is known as the Leontief inverse and is also of dimensions $nN \times nN$. Coefficient $l_{ir\to js}$ of the Leontief inverse quantifies how much input from sector i in country r is needed both directly and indirectly to produce one unit of output for sector j in country s. $\mathbf{e}$ is a $N \times 1$ column vector of ones, i.e. the summation operator. The final demand matrix $\mathbf{Y}$ is of dimensions $nN \times N$. Element $y_{ir\to s}$ is the final demand for commodity i produced in country r stemming from country s. This element corresponds to the $(r-1)n+i$-th row, s-th column of the $\mathbf{Y}$ matrix. Hence, the s-th column of the final demand matrix represents the final demand for all commodities in country s.

We note $\mathbf{Y}^s$ the $nN \times N$ final demand matrix for country s, where all columns except for column s are set to 0. Using this notation, the final demand matrix $\mathbf{Y}$ can be written as the sum of the N national demand matrices:

$$\mathbf{Y} = \sum_{s=1}^{N} \mathbf{Y}^s. \tag{2}$$

In what follows, we denote $\mathbf{q}$ as the row vector of dimensions $1 \times nN$ quantifying the externalities directly caused by each sector per unit of output, in which element q_{ir} corresponds to the quantity of externalities per unit of output caused by sector i in country r. As for the final demand $\mathbf{Y}$, we can write the vector $\mathbf{q}$ as the sum of N national vectors of externalities coefficients:

$$\mathbf{q} = \sum_{r=1}^{N} \mathbf{q}^r, \tag{3}$$

where $\mathbf{q}^r$ is the vector of direct externalities coefficients for country r, in which all coefficients associated with countries $s \neq r$ are set to 0.

The volume of externalities caused in in country r to supply the final demand in country s can be obtained by multiplying the vector of externalities coefficients of country r, $\mathbf{q}^r$ with the Leontief inverse $\mathbf{L}$ and the final demand in country s, $\mathbf{Y}^s$:

$$f_{rs} = \mathbf{q}^r \mathbf{L} \mathbf{Y}^s \mathbf{e}. \tag{4}$$

The sum of the externalities caused in country c to supply the final demand in any country corresponds to the Production Based Accounting (PBA) measure of the externalities attributable to country c, noted $pba^{\boldsymbol{c}}$:

$$pba^c = \sum_{s=1}^{N} f_{cs} = \sum_{s=1}^{N} \mathbf{q}^c \mathbf{L} \mathbf{Y}^s \mathbf{e}. \tag{5}$$

According to equation (2), equation (5) becomes:

$$pba^c = \mathbf{q}^c \mathbf{L} \mathbf{Y} \mathbf{e}. \tag{6}$$

Reciprocally, the sum of the externalities caused in any country to supply the final demand in country c yields the Consumption Based Accounting (CBA) measure of that country, i.e., is the volume of externalities caused both directly and indirectly to supply the final demand of country c, noted cba^c:

$$cba^{\mathrm{c}} = \sum_{r=1}^{N} f_{rc} = \sum_{r=1}^{N} \mathbf{q}^r \mathbf{L} \mathbf{Y}^c \mathbf{e}. \tag{7}$$

Using equation (3), the CBA measure of country c can finally be written has:

$$cba^c = \mathbf{q} \mathbf{L} \mathbf{Y}^c \mathbf{e}. \tag{8}$$

Measuring the *throughflow*

We define the *throughflow* as the result of the Hypothetical Extraction Method (HEM) applied to externalities accounting. The HEM compares a counterfactual of the global economy where a group of economic sectors or a country is assumed not to exist to the actual global economy, to identify the importance of the excluded economic sectors or countries (Dietzenbacher et al., 1993; Miller & Blair, 2009, pp. 563–565). In order to define the throughflow, we apply the HEM in such a way that all upstream externalities generated by supply chains either starting from, passing through or ending in a given country are considered, in line with the interpretation from Hanaka et al. (2022) and Tokito et al. (2022).

In order to formalize the measure of the throughflow, we need to introduce some additional notations. From the matrix of input coefficients $\mathbf{A}$, we derive the matrix of input coefficients *in absence of a given country* c, $\bar{\mathbf{A}}^c$. In comparison with the matrix $\mathbf{A}$, the coefficients corresponding to inter-industry relations within c, imports to c and exports from c are set to 0 (i.e., the $(c-1)n$-th to cn-th rows and columns are set to zeros):

$$\bar{\mathbf{A}}^c = (\bar{a}^c_{ir\to js}) = \begin{cases} 0 \; if \; r = c \; or \; s = c \\ a_{ir\to js} \; otherwise \end{cases}. \tag{9}$$

Based on the matrix of input coefficients *in absence of country* c, we define the Hypothetically Extracted Leontief inverse $\bar{\mathbf{L}}^c$ as:

$$\bar{\mathbf{L}}^c = (\mathbf{I} - \bar{\mathbf{A}}^c)^{-1}. \tag{10}$$

The Hypothetically Extracted Leontief inverse describes the direct and indirect inputs needed to produce one unit of output in a hypothetical economy where country c were removed.

Then, we define $\bar{\mathbf{Y}}^c$ to be the global final demand of commodities outside of country c, built from the final demand matrix $\mathbf{Y}$ by setting the final demand of country c (c-th column) to zero:

$$\bar{\mathbf{Y}}^c = \mathbf{Y} - \mathbf{Y}^c = \sum_{s \neq c} \mathbf{Y}^s. \tag{11}$$

Likewise, we define $\bar{\mathbf{q}}^c$ to be the row vector of externalities produced outside of country c, by setting the externalities production from country c to zero:

$$\bar{\mathbf{q}}^c = \mathbf{q} - \mathbf{q}^c = \sum_{r \neq c} \mathbf{q}^r. \tag{12}$$

Following the interpretation of the HEM by Hanaka et al. (2022) and Tokito et al. (2022), we formally introduce the scalar **throughflow**[2] tba^c as the volume of externalities identified with the HEM for country c:

$$tba^c = (\mathbf{qLY} - \bar{\mathbf{q}}^c \bar{\mathbf{L}}^c \bar{\mathbf{Y}}^c)\mathbf{e}. \tag{13}$$

Decomposing the throughflow

Using these notations, we can identify four flows of externalities forming the throughflow: *local*, *imported, exported* and *traversing externalities*[3].

The volume of externalities caused by local supply chains (*local externalities*) are captured by the scalar loc^c:

$$loc^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = f_{cc}. \tag{14}$$

These externalities are caused in country c for the production of commodities finally used in country c. Note that this flow of externalities can be further decomposed into two elements, depending on whether the supply chains causing these externalities traverse other countries (*re-imported externalities*) or not (*purely local externalities*, see Supplementary Materials equations S.7-8).

The column vector of externalities caused by importing supply chains (*imported externalities*, $\mathbf{imp}^c$), of dimensions $N \times 1$, identifies the externalities generated abroad by supply chains ultimately

[2] We also propose a spatially explicit formulation of the throughflow in the Supplementary Materials (equation S.1). Element tba_{rs}^c of such *throughflow matrix* captures the externalities caused in country r to supply the final users in country s through country c. This alternative formulation is coherent with the forthcoming TBA decomposition (see equation. S.4).

[3] The terms used to define the components of the TBA decomposition are to be understood in a figurative way. The mention of *imported/exported/traversing externalities* do not refer to externalities being physically traded between countries, but rather to externalities generated to produce traded commodities. Such externalities associated with trade flows are sometimes referred to in the literature as *embodied externalities* (Skelton et al., 2011; Wood et al., 2018; Zhang, Guan, et al., 2020). As this formulation has been criticised for being ambiguous (Jakob & Marschinski, 2013; Liu, 2015; Jakob et al., 2021), we refrain from using it in this manuscript.

serving final consumers in country c. Its elements are defined as follows for all countries r different from country c[4]:

$$imp_r^c = \mathbf{q}^r \mathbf{L} \mathbf{Y}^c \mathbf{e} = f_{rc}. \tag{15}$$

Coefficient imp_r^c captures the volume of upstream externalities caused in country r to supply the final demand in country c.

The row vector of externalities caused by exporting supply chains (*exported externalities*, $\mathbf{exp}^c$), of dimensions $1 \times N$, represents the externalities caused in country c by supply chains reaching final consumers abroad[5]:

$$exp_s^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^s \mathbf{e} = f_{cs}. \tag{16}$$

Coefficient exp_s^c captures the upstream externalities caused in country c to supply the final demand in country s.

Finally, the matrix of externalities caused by traversing supply chains (*traversing externalities,* $\mathbf{TRA}^c$), of dimensions $N \times N$ identifies the externalities caused abroad for supplying final demand abroad, but whose associated supply chain involves country c at least once[6]:

$$tra_{rs}^c = \mathbf{q}^r (\mathbf{L} - \bar{\mathbf{L}}^c) \mathbf{Y}^s \mathbf{e}. \tag{17}$$

Here, coefficient tra_{rs}^c measures the externalities caused in country r to supply the final demand in country s *through* country c.

From these definitions, we define the **Throughflow Based Accounting** (TBA) as the following decomposition of the throughflow (see fig. 1 for illustration and the Supplementary Materials equations (S.9-17) for the demonstration):

$$tba^c = loc^c + |\mathbf{imp}^c| + |\mathbf{exp}^c| + |\mathbf{TRA}^c|, \tag{18}$$

where the symbol | | indicates the sum of all the coefficients of the corresponding matrices or vectors, i.e., the summation operator.

Relation with other accounting frameworks

The TBA decomposition (equation 18) explicitly contains the elements forming the PBA (5) and CBA (7) frameworks, through the element loc^c (14) and the vectors $\mathbf{exp}^c$ (16) and $\mathbf{imp}^c$ (15), respectively. By construction, both PBA and CBA frameworks can be formally expressed using the components of the TBA:

$$\begin{cases} pba^c = loc^c + |\mathbf{exp}^c|; \\ cba^c = loc^c + |\mathbf{imp}^c|. \end{cases} \tag{19}$$

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[4] The externalities caused in country c for supplying the final demand in country c are counted as *local externalities*. Therefore, by convention, $imp_c^c = 0$.

[5] For the same reason that $imp_c^c = 0$, $exp_c^c = 0$: the flow of *exported exernalities* only capture externalities caused for supplying the final demand in countries *other than country* c.

[6] Again, the definition of traversing externalities only covers the externalities caused in countries *other than country* c for supplying the final demand in *other countries than country* c. Thus, for any country r and s, $tra_{cs}^c = tra_{rc}^c = 0$.

The TBA decomposition is largely comparable to the decomposition of the HEM proposed by Hanaka et al. (2022), except that the latter is defined at the sector scale and distinguishes between intermediate and final trade (see Supplementary Materials). Regarding BBA (Liang et al., 2016), TBA differs in two main aspects. First, there is to our knowledge no formulation of the betweenness at the scale of a country (or more broadly at the scale of a group of sectors). Second, the TBA being based on the HEM, it counts supply chains only once, even when such supply chain traverses the same country more than once (Tokito et al., 2022) (Fig. S.1).

Finally, there is a similarity between the framework proposed here and the Global Value Chain (GVC) literature. In particular, the TiVA framework allows identifying the domestic and imported value-added content in the gross exports of a country (Koopman et al., 2010, 2014; Borin & Mancini, 2019), which are related to the *exported* and *traversing* elements of our decomposition, respectively. Beyond an obvious difference in scope (TiVA usually focuses on Value Added, while the TBA is defined for any externality), the TiVA and TBA decompositions differ in their respective perspective. While the TiVA decomposition is usually defined from gross exports (Koopman et al., 2010, 2014) or from bilateral trade flows (Borin & Mancini, 2019), the TBA is defined from the global final demand (equation (13)). Additionally, the TiVA decomposition allows distinguishing in exports and imports between the direct trade partner and the final consumer, while the TBA only allows the identification of the countries where externalities production and final consumption occur. Similarly, the TBA framework does not identify the double counted externalities associated with self-looping supply chains (fig. S.1), nor differentiates between the trade of intermediate and final commodities.

Study case: The CO_2 throughflow of Germany

This section demonstrates the added value of the TBA framework by quantifying the upstream CO_2 emissions generated by the supply chains originating from, passing through or ending in Germany. We use EORA26 (Lenzen et al., 2012, 2013) for the year 2015 as MRIOT and CO_2 emissions from the Primap databases (Gütschow et al., 2020, 2021). The Primap databases contain CO_2 emissions data at different levels of sectoral and geographical detail. Using a tailored algorithm (see Supplementary Materials), we combine data from the Primap hist (Gütschow et al., 2021) and Primap crf (Gütschow et al., 2020) data sets with MRIOT data from EORA26 to allocate direct CO_2 emissions to the 26 sectors and final demand covered in the EORA26 MRIOT, from the 182 countries covered in the Primap hist database. We ignore in what follows the direct emissions from final users (e.g., CO_2 emissions from individual cars), since those emissions are not related to further processing steps.

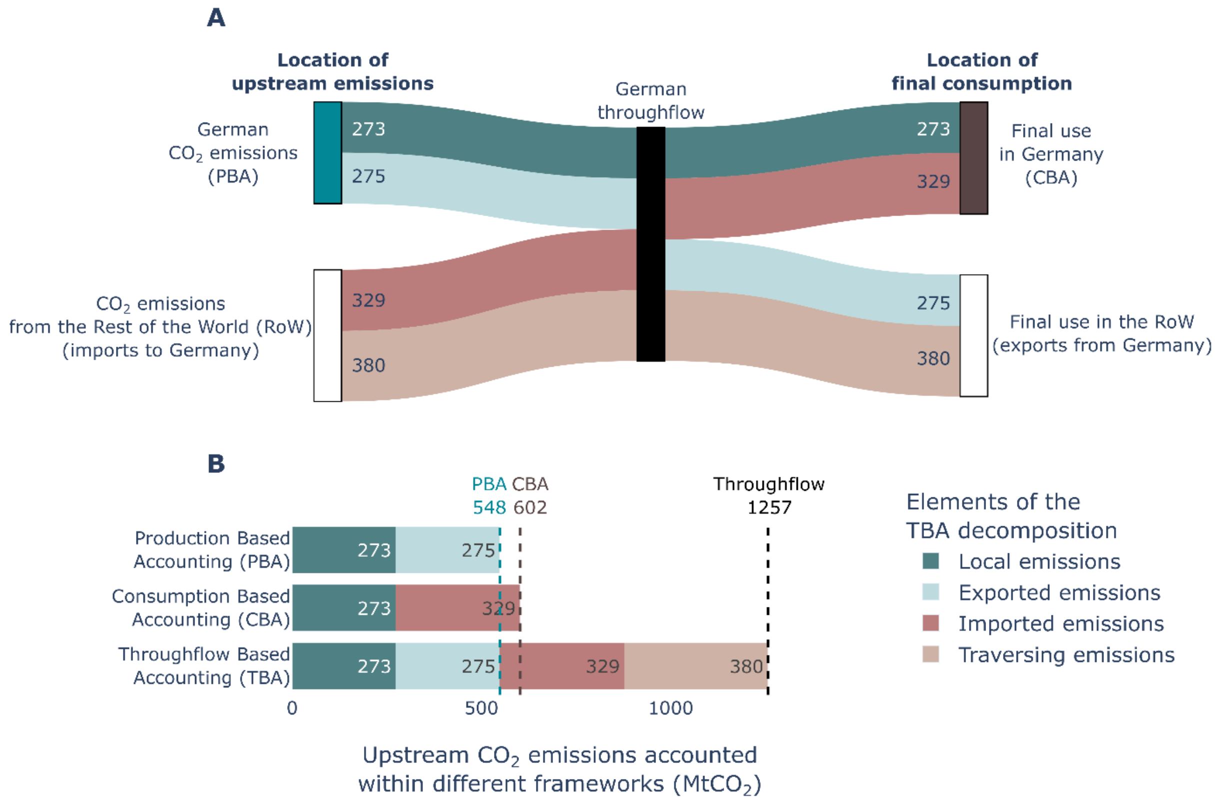

Figure 2 – TBA decomposition of the German CO_2 throughflow. *A. Representation of the Throughflow Based Accounting (TBA) decomposition of the German CO_2 throughflow, in 2015. The width of the links is proportional to the volume of upstream CO_2 emissions captured by the corresponding element of the TBA decomposition. The numerical values are indicated on the links, in $MtCO_2$. The bars on the left indicate whether CO_2 emissions have occurred in Germany (upper left bar) or in the rest of the world (RoW, bottom left bar). The bars on the right show where the final commodities causing these CO_2 emissions are finally used, either in Germany (upper right bar) or in the RoW (bottom left bar). The black, central bar indicates the German throughflow, i.e., the volume of upstream CO_2 emissions generated by the supply chains Germany is involved in. B. Decomposition of the CO_2 emissions allocated to Germany in the PBA, CBA and TBA frameworks. The values refer to the volume of upstream CO_2 emissions measured by the different elements of the TBA decomposition, in Mt of CO_2. The dashed line indicates the total volume of CO_2 emissions allocated to Germany within each framework.*

Overall, we find that the TBA framework identifies substantially more CO_2 emissions than the usual accounting frameworks (fig. 2). We estimate the total throughflow of CO_2 of Germany to 1.26 Gt of CO_2, more than twice the quantities measured in both the CBA and PBA frameworks. Through its involvement in international supply chains, the German economy is linked with substantially more CO_2 than just those generated on its territory (PBA, fig. 2A) and those generated to supply its final consumption (CBA). Within our perimeter of CO_2 emissions (i.e. omitting direct emissions from final consumers), we estimate the quantity of CO_2 emissions directly emitted from within the German territory to be 548 Mt (PBA; fig. 2B). About half of these emissions, i.e. 275 Mt, are emitted to produce or process commodities that are consumed elsewhere in the world (*exported emissions*). For instance, this volume includes the CO_2 emitted by a German power plant to produce a car that is sold abroad. Reciprocally, 329 Mt of CO_2 are emitted abroad to process commodities that are ultimately consumed in Germany (*imported emissions*). As an illustration, the CO_2 emitted to produce steel beams in China that are used to maintain the German railway is included in this flow of imported emissions. Because of the imbalance between the emissions generated to produce German's exports and imports, the volume of CO_2 emitted to supply the final demand in Germany (CBA) amounts to 602 Mt of CO_2, around 10% higher than the PBA measure.

However, considering either PBA or CBA alone masks a substantial volume of CO_2 emissions associated with the German economy. Two elements explain this gap between the German PBA/CBA and TBA totals. First, PBA (CBA) accounts for the emissions generated to process German exports (imports) but omits emissions generated for its imports (exports). With regard to the examples introduced previously, the CO_2 emissions caused by the foreign steel production for the German railway do not count into the PBA account of CO_2 emissions for Germany; and the German emissions to produce cars for exports are not accounted for in a CBA-type assessment. TBA, however, includes emissions generated for both exports and imports. Second, both CBA and PBA do not account for emissions associated with supply chains going through the German economy (*traversing emissions*). An illustration of such emissions is the CO_2 emitted abroad for producing aluminum, which is further used in Germany to produce cars finally sold abroad. We find that these emissions amount to 380 Mt of CO_2 in Germany, i.e., the same order of magnitude as German *exported* and *imported* emissions.

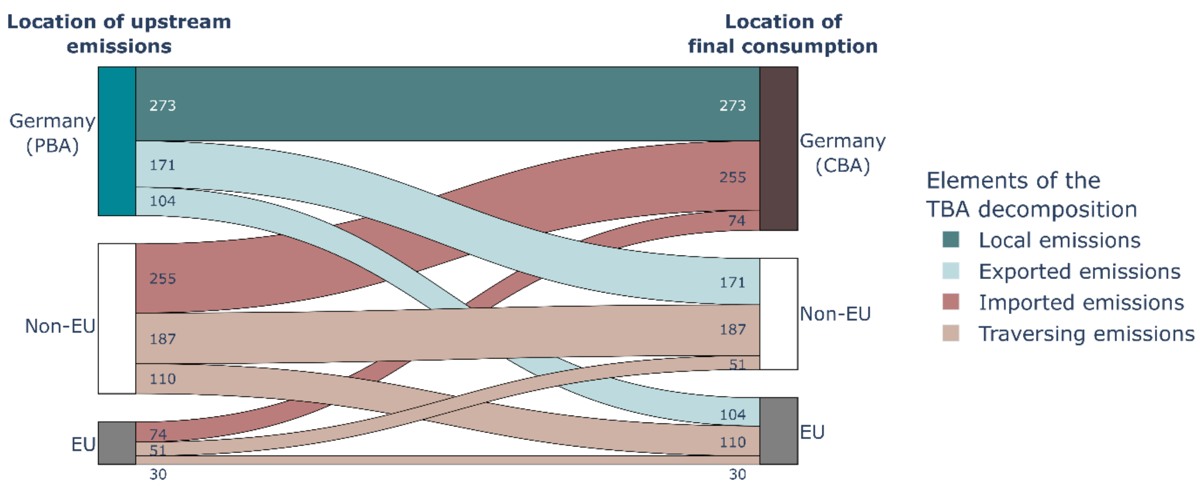

Figure 3 – Origin and destination of the supply chains causing the German throughflow of CO_2 emissions. *As in fig 2A, the left blocks show where CO_2 emissions associated with the German economy (i.e., Germany's throughflow) were originally emitted. The right blocks indicate where the commodities associated with these emissions were finally consumed. In comparison to fig. 2A, the Rest of the World (RoW) is here decomposed into countries members of the European Union (EU) and non-EU countries. The width of the flows is proportional to the volume of CO_2 emissions measured. The numbers indicate the volume of upstream CO_2 emissions captured by the correspond element of the TBA decomposition, in Mt CO_2. Colouring of links corresponds to the different components of the throughflow, as introduced in fig. 2. Table S.1 in the Supplementary Materials presents the data in tabular form.*

A closer look at the German throughflow shows that the German economy is linked to a large volume of CO_2 emissions occurring outside of the EU (fig. 3). More than three times more CO_2 is emitted in non-EU countries (255 Mt CO_2) than in EU countries (74 Mt CO_2) to supply the final demand in Germany. The contribution of non-EU CO_2 emissions to Germany's final demand is comparable to the volume of emissions caused in Germany itself (273 Mt CO_2). A similar relation holds for the emissions caused by supply chains traversing the German economy. For supplying the final demand in other EU countries, Germany is contributing to more CO_2 emissions in the rest of the world (110 Mt CO_2, e.g. emissions caused to prepare the Chinese aluminum used to produce German cars) than in Germany itself (104 Mt CO_2, e.g., emissions from coal burning for powering German car manufactures) or in other EU countries (30 Mt CO_2, e.g., emissions to manufacture spare parts of German cars in Poland). Finally, the supply of the final demand in non-EU countries via the German economy is causing almost twice as much CO_2 emissions (409 Mt CO_2) as those caused to supply the final demand in other EU countries (244 Mt CO_2). The formers are mainly caused in non-EU countries (187 Mt CO_2) and in Germany (171 Mt CO_2), but only marginally in other EU countries (51 Mt CO_2). Therefore, the trade of emission-intensive commodities from and to Germany appears to be more largely related to non-EU countries than to other EU member states.

The TBA decomposition also gives insights on the position of a country's economy in global supply chains. Figure 4A shows, for each of Germany's trade partners, which share of their emissions supplies final users in Germany (*imported emissions*) relative to all of their emissions caused by supply chains going through Germany (*imported and traversing emissions*). For instance, around 70% of CO_2 emissions induced in South-Eastern Asian countries by supply chains involving Germany are caused by the German final demand (*imported emissions*). As an example, such emissions include those required to produce textile in Laos, which is further sold in Germany. By opposition, most emissions related to the German economy in fossil fuel producing countries serve the production of final commodities consumed outside of Germany. Only 31% of the CO_2 emissions from Libya and Kazakhstan, 37% of the Russian emissions are used to supply the German final demand (*imported emissions*), for instance for powering domestic heating systems. The rest of it (69% in Libya and Kazakhstan, 63% in Russia) is further incorporated in German exports (*traversing emissions*). For instance, emissions caused by the extraction of oil and gas in Russia may serve powering a car factory in Germany, whose cars are further sold abroad.

Reciprocally, figure 4B indicates, for the supply chains going through Germany and supplying the final demand in each country (*exported and traversing emissions*), which share of the upstream emissions caused by these supply chains happened in Germany (*exported emissions*). While the position of the German economy with regard to the creation of emissions in other countries is very heterogeneous (fig. 4A), the origin of the emissions to supply the final demand in other countries via the German economy is rather similar from one country to another (fig. 4B). The CO_2 emissions caused by the German economy to supply the final demand of other countries are caused either in Germany (from 40% and 50% of all emissions generated) or in the rest of the world (from 50% to 60%). An example of emissions caused in Germany to supply another country's final demand (*exported emissions*) are the emissions from German gas plants to power car factories whose product is ultimately sold abroad. Conversely, the emissions related to the extraction of gas in Russia are associated with *traversing emissions*.

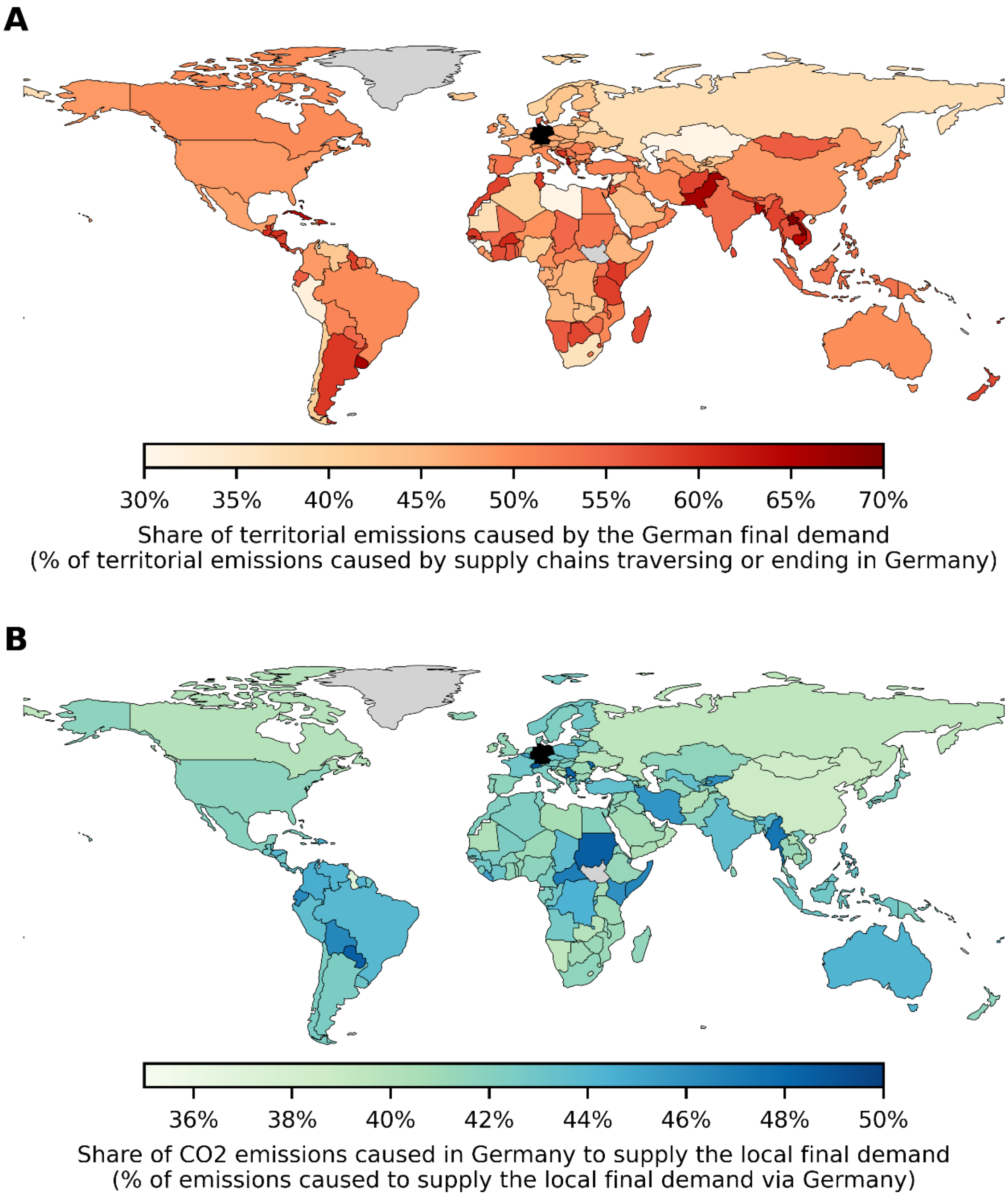

Figure 4 – Position of the German economy in supply chains generating CO_2 emissions. *A. Indication of the role of the German economy in the supply chains causing territorial emissions. Colouring of countries indicates the share of emissions generated in these countries to supply the German final demand (imported emissions), as a percentage of all emissions generated along the supply chains involving the German economy (imported and traversing emissions). B. Indication of the role of the German economy in supplying the final demand of other countries. The colour of a country shows the share of emissions caused in Germany to supply the final consumption in that country (exported emissions), as a percentage of all emissions caused to supply the final demand of that country via the German economy (exported and traversing emissions). Germany is shown in black. Countries for which no data are available are shown in grey.*

Discussion

In this section, we discuss the findings of the previous section and we explore the types of policy options that the different elements of the TBA may help to design. In the previous section we have applied the TBA framework to assess all upstream CO_2 emissions caused by the supply chains associated with the German economy. Specifically, we estimated the German CO_2 throughflow, i.e. the upstream emissions caused by supply chains originating from, passing through or ending in Germany, to be 1.26 Gt CO_2. Some but not all of these emissions could have been identified using alternative accounting techniques.

First, *local* and *exported* emissions could have been identified by means of the PBA framework. They are generated within the country and and are thus the emissions a country has the most control on, as direct policy measures can be implemented domestically to limit them, e.g. by regulating the use of the most polluting processes, by supporting the adoption of cleaner technologies or by enforcing a carbon price on domestic production. Second, *imported emissions* could have been identified using the standard CBA framework (Peters, 2008; Davis et al., 2011; Kagawa et al., 2015). These emissions are more challenging to address, as they are produced abroad. Consumption-side policies may be implemented to curb the use of the most emissions-intense commodities, for instance using consumption taxes or by informing the final users about the emissions caused abroad. Such consumption-side policies may also contribute to reducing the emissions caused by *local* supply chains, as these are also dependent on domestic final consumers. While the TBA is conceptually coherent with both the PBA and CBA frameworks, the exact figures we obtain for PBA and CBA in our case study may differ from those found in other studies because of the use of different primary data sources and because of differences in accounting perimeters. For instance, our figures do not include direct emissions from final users, nor emissions from international transportation.

Finally, supply chains *traversing* the German economy are causing emissions abroad and do not supply domestic final users. These emissions are thus not revealed by the PBA and CBA frameworks and left unaddressed by both production-side and consumption-side policy measures, even though they represent 30% (379 Mt CO_2) of the German throughflow according to our analysis. Such emissions could be targeted through supply chain specific measures, for instance by changing production processes to reduce the usage of the most emissions-intensive inputs or by sourcing these inputs from relatively low-carbon producers. Such supply chain specific policy options are usually explored using SPA, BBA or related frameworks (Liang et al., 2016; Hanaka et al., 2017; Maeno et al., 2022). As SPA and BBA techniques double count emissions caused by supply chains that loop into the German economy several times, these techniques may indicate higher volumes of CO_2 emissions than identified here. BBA or SPA frameworks may often be better suited for investigating supply chain specific policy actions than a HEM-based framework such as ours or such as the one proposed by Hanaka et al (2022) because productivity improvements in one sector may have a multiplier effect if such sector is involved in several production steps of the same supply chain (Tokito et al., 2022).

Alternatively, *traversing emissions* could be targeted through the implementation of a comprehensive carbon pricing policy. While usual carbon pricing schemes only apply to domestic emissions, the implementation of Border Adjustment Mechanisms (BAMs) allows extending the carbon price to imported products as well (Sakai & Barrett, 2016; Böhringer et al., 2022). In such a case, the carbon price would cover both *local, exported, imported* and *traversing* emissions, hence corresponding to the whole throughflow. Conversely, the introduction of export rebates could be helpful to preserve the competitiveness of domestic companies and would relieve *exporting* and *traversing* supply chains from the carbon price (i.e. covering the emissions measured by CBA only). Because of the problem of double counting, BBA, SPA and related methods are not applicable to comprehensive carbon taxation analysis. However, techniques usually applied to investigate the TiVA (Koopman et al., 2010, 2014; Los & Timmer, 2018; Borin & Mancini, 2019) could theoretically be used to derive the volume of CO_2 emissions traversing the German economy as done in the TBA, although we are not aware of any such study at the time of writing this paper. Meng et al. (2018) have used TiVA methods to investigate the share of foreign CO_2 emissions in Germany's gross production. Using MRIO data from 2009, they estimate that 35% of the emissions required to produce final goods and services in Germany are caused outside of Germany. This measure is not directly comparable to the throughflow due to a different framing : Meng et al. (2018) focus on emissions caused by the production of final commodities in Germany, while the throughflow includes the production of intermediate commodities as well. In the TBA, we measure the share of foreign emissions (i.e., *imported* and *traversing* emissions) to amount to 56% of the total production of products and services in Germany (i.e., the German *emission throughflow*). The inclusion of intermediate products may partly explain the difference between our result and the one from Meng et al. (2018) but the use of a different and older MRIOT is likely to contribute to this difference as well. Overall, both the TiVA methods and the TBA are applicable for investigating the implementation of BAMs, as both approaches exclude counting the same emissions multiple times. The TiVA methods are in principle more flexible than the TBA, as they can be applied to specific trade relations. Conversely, the TBA provides a broader and more intuitive overview of the emissions a country could target through its supply chains' involvement.

Finally, we used the TBA decomposition of the German CO_2 throughflow to derive insights into the position of Germany in carbon-intensive Global Value Chains (GVCs). Our finding that Germany is a major emission hub both at the EU and at the global scale is coherent with more general studies on the position of the German economy in GVCs (Godard & Gorg, 2011; Los et al., 2015; Amador & Cabral, 2017; Xiao et al., 2020). However, in these studies, the German economy is shown to be trading in the same proportions with European than with non-European countries. Our results show instead a stronger representation of non-EU countries than EU countries in the CO_2 emissions caused by German exports and imports (see fig. 3). Beyond divergences in primary data sources, differences in emission intensities between EU and non-EU countries may be an explanation for the difference between our results and the pre-existing literature, as supply chains originating from non-EU countries are usually more carbon-intense than those originating from other EU countries.

Conclusion

We here introduced the throughflow as the volume of upstream externalities generated by the supply chains a country is involved in; that is, the externalities generated along supply chains starting from, traversing or ending in a given country. We further defined the Throughflow Based Accounting (TBA) as the decomposition of the throughflow based on the origin and the destination of the supply chains causing these externalities. TBA has a broader perimeter than the commonly used externalities accounting frameworks: it accounts for externalities directly produced in a country (as in Production Based Accounting), for externalities induced by the final consumption in a country (as in Consumption Based Accounting) and for externalities caused by the supply chains traversing that country (related to Betweenness Based Accounting, BBA). TBA hence captures all externalities that could be targeted by a country, either through supply-oriented, demand-oriented or trade-oriented policy actions. In comparison to other accounting techniques based on the Hypothetical Extraction Method (Koopman et al., 2010, 2014; Los & Timmer, 2018; Borin & Mancini, 2019; Hanaka et al., 2022), the TBA decomposition is based on only four intuitive elements. While such simple framework comes with limitations, it renders the TBA straightforward and easily applicable beyond the Input-Output community.

The TBA gives a comprehensive overview of the upstream externalities a country could target through the supply chains it is involved in. Beyond international supply chains, there are other channels a country could explore to target externalities beyond its border, for instance via diplomatic efforts or via technology transfers (Ward et al., 2017). Similarly, the TBA only accounts for *upstream* externalities, i.e., externalities which have been produced at earlier stages of the supply chains. The TBA does not account for *downstream* externalities, i.e., externalities caused in further stages of the supply chains. For instance, limiting the trade of fossil fuel (Peters et al., 2012) or allocating primary inputs to less CO_2-intensive companies (Liang et al., 2017) have both a major potential for *downstream* mitigation of CO_2 emissions. Also, the TBA does not capture how many borders a supply chain is crossing (Zhang et al., 2017; Zhang, Zhang, et al., 2020), which could be useful for assessing how directly other actors in international supply chains would be affected by local policy decisions.

Beyond estimating the volume of externalities a country could target through its supply chains, the estimation of the impact of actual policies requires dynamic approaches that go beyond the scope of this method. In particular, the reduction of the throughflow of a country may not necessarily coincide with a reduction of global negative externalities. For instance, Jakob and Marschinski (2013) show that reducing the imports of emissions-intensive commodities does not necessarily reduce global emissions, as the substitution of imports by domestic production may be more emissions-intensive. Similarly, shrinking the throughflow of one country does not necessarily reduce the global production of a negative externality. For instance, a diminishing throughflow in one country may simply be associated with a symmetrical increase of another country's throughflow as a result of the redirection of supply chains through this other country. A rudimentary integration of dynamic mechanisms in the TBA framework, as already envisioned for the PBA and CBA frameworks (Jakob et al., 2021), could acknowledge the flexibility of the global trade relations and provide more detailed insights into the power of intermediates to influence externalities production elsewhere.

As an intelligible flow-based approach, the TBA can readily be used to inform policy- and decision-makers on the potential for negative externalities mitigation by consumers, producers, and intermediates across the world. In the climate change mitigation debate, the fragmentation of the global trade regime has made the case for local policy measures to reduce emissions globally more attractive (Jakob et al., 2022): policy options to reduce carbon emissions abroad such as Carbon Border Mechanism Adjustments are now discussed in the EU (*"Fit for 55": Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality*, 2021). By straightforwardly identifying all the emissions caused by supply chains going through the EU economy, the TBA can be used to identify the countries which would be impacted by such measures.

Disclosure statement

The authors have no competing interest to declare.

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Data availability statement

Data generated to conduct the study will be made available through an online depository at the publication of the research, including links to raw data from external sources and the scripts used to generate the data and to create the figures.

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