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On the fair accounting of carbon emissions in the global system using an exergy cost formation concept

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A B S T R A C T

Carbon accounting is necessary for designing effective climate change mitigation policies. A proper and fair accounting method should motivate both the producers toward cleaner production methods and the consumers toward reducing the embodied emissions of their consumption. This research work proposes a new approach to map the production chain of carbon emissions in which every subsystem is responsible for the level and efficiency of its production activities and embodied emissions for providing its economic activities or final demands. The exergy cost formation concept is used to track the emissions in the production chain. The results of this accounting present the total carbon loads on economic outputs either consumed locally or exported abroad (CExA). The CExA results are then compared to the results of conventional production-based (PBA) and consumption-based (CBA) carbon inventories. Here we show that, in addition to the levels of production and consumption, the economic structures of the countries and the efficiency of the production activities are important factors differentiating the roles of the countries in the global emissions. Our results show that the share of the imported emissions to the total CExA varies between 14% for developing countries to 34% for the developed countries. Moreover, although the ratio of CBA to PBA for the countries is highly dependent on their economic states (0.87 for developing countries and 1.21 for developed countries), the ratio of CExA to PBA does not follow a unique trend among developing or developed countries. The results demonstrate that, according to the proposed sharing approach, the import-oriented developed countries, which have benefited the most from the carbon leakage effect, are mostly penalized for the embodied emissions associated with the imports to their economy, and vice versa.

1. Introduction

Climate change has been one of the most controversial and common environmental concerns about the quality of life of human beings. The problem is huge in extent and requires an integrated action plan involving the participation of all nations in accordance with "the common but differentiated responsibilities and respective capabilities" (UNFCCC, 1992). Sharing responsibilities has been one of the most debated issues of acting against climate change in global negotiations. This is due to the fact that there is no agreement on the fair perception of the contributions of different countries in causing the problem. Therefore, climate equality has been the subject of numerous research works. It is widely accepted that in a fair allocation of the global responsibilities to the climate change, factors such as the past and current shares of greenhouse gases (GHG) emissions should be considered. Moreover, one main issue refers to the differences in the assigned responsibilities resulting from different carbon accounting approaches.

The allocation of the responsibilities must be proportional to the shares in the global GHG emissions and the corresponding global resource consumptions. There are several approaches applicable to such accounting (Eder and Narodoslawsky, 1999). Conventional allocation approaches have been developed based on the direct emissions from a country territory (Territory-Based Accounting (TBA)), direct emissions resulted from value-added production of the countries (Production-Based Accounting (PBA)), and the direct (local) and indirect (embodied in trades) emissions to meet the final demands of a nation (Consumption-Based Accounting (CBA))

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Abbreviations

BRIICS (BRIIS)	Major developing countries -Brazil, Russia, India, Indonesia, South Africa-including (excluding) China
CBA	Consumption-Based Accounting
CEA	Carbon Emission Added
CExA	Carbon Emission Added based on the exergy cost accounting
FCBA	Full Consumption Based Accounting
G7	Group of 7 (most advanced economies): Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States
GHG	Greenhouse Gases
ICIO	Inter-Country Input-Output tables
ISIC	International Standard Industrial Classification
MRIO	Multiregional Input-Output tables
OECD	Organization for Economic Co-operation and Development
PBA	Production-Based Accounting
RoW	Rest of the Wolrd
SBA	Shared-Based Accounting
TBA	Territory-Based Accounting

Nomenclature

*CEA**	Cumulated Carbon Emission Added (t CO_2e/yr)
E	Total embodied emission associated with a stream (t CO_2e/yr)
E	Cumulated carbon intensity (g CO_2e/MJ)
ExC	Cumulative exergy destruction (MJ/$)
S	Economic Sector
V	Monetary value of product ($)
Y	Total direct emissions as in PBA (t CO_2e/yr)

Subscripts

i	Index referring to an exporting country
j	Index referring to an importing county
k, l	Index referring to an economic sector (product)

(Peters, 2008). The later, also known as the carbon footprint, is introduced as the emissions embodied in the final demands (Peters and Hertwich, 2008). Hence, this is equal to the local emissions (PBA) plus the emissions embodied on the imported final products minus the embodied emissions of exports (Wiebe and Yamano, 2016). These approaches have different levels of complexities in calculations, data requirements, and uncertainties. Moreover, when applied to the question of allocation of the responsibilities, they are biased toward benefits of the producers or consumers. In the PBA (as well as the TBA), the producers are the sole responsible body for GHG emissions, while in the CBA, all the emission loads are assigned to the final consumers (Davis and Caldeira, 2010). Therefore, although the CBA can complement the functionality of PBA for raising awareness of the societies about the impacts of their actions and consumptions, yet it is not clear how to combine the two indicators for effective policy implications (Afionis et al., 2017).

In a fair allocation of responsibilities, the countries should bear the whole environmental burden resulting from all the supplies and demands necessary for their economic growth (Lenzen et al., 2007). In this case, every nation is responsible for the climate externalities of the desired increase of its welfare. This environmental burden is caused by either the direct emission of the pollutants from the production activities or indirectly by the import of the products or services which had caused upstream emissions abroad. Ignorance of the responsibilities from the consumption of the imported products has lad to the shift of the carbon-intensive productions from developed countries (with restricted climate commitments) to developing countries (Rothman, 1998). This effect, also called "*carbon leakage*", has continuously increased since 1990 (Peters et al., 2011). Many researchers (e.g., Wiebe and Yamano (2016)) have shown the extent of carbon leakage among different categories of the countries. The leaked carbon could be as high as 26% of total global emissions (Peters et al., 2011). This effect has been understood as a result of the PBA-based climate change policies in the past decades. The balance of the embodied carbon on trades depends on the development stage and the corresponding economic structures of the countries (Davis and Caldeira, 2010). Therefore, a proper accounting method should consider both the production and consumption responsibilities of the local emissions and the emission loads on the imported materials and services.

Accordingly, another group of accounting methods has been developed to reduce the inefficiencies of the PBA and CBA methods by *sharing* carbon loads in trades between consumers and producers (SBA). In contrast to the CBA, the SBA methods do not exclude the embodied emissions of the exported materials and services from the producer responsibilities. This is done through modifications in the CBA by either sharing the embodied emissions of exports among the producer and consumer based on the relative added values for the producers and consumers, e.g., by Lenzen et al. (Lenzen et al., 2007; Marques et al., 2012; Rodrigues and Domingos, 2008) or by assigning the share of embodied emissions resulting from inefficient production operations to the producer, e.g., (Kander et al., 2015).

This paper aims at developing and implementing a new SBA method. There uncertainties in sharing the added values from trades among producers and consumers (Kander et al., 2015). Also, there is possibility of failure in considering the economic incentives for climate policy implications (Jakob and Marschinski, 2013). Therefore, the proposed method is based on the notion that the desirability of trade is identical for both the supply and demand sides. As a result, both the producer and the consumer are equally responsible for the embodied emissions of a traded stream. A detailed discussion of the implemented methods is presented in the next section of this paper.

Assigning responsibilities can facilitate the identification of fair contributions of the countries in financing global action plans. However, the implications in policy implementation techniques have been widely discussed in the literature and are out of the scope of the present work.

2. Methodology

In any sharing carbon accounting approach, the way of assigning the carbon loads on the traded streams differentiates the SBA approaches from one another and from the CBA and PBA inventories. Two main factors affect the role of individual nations in emitting greenhouse gases: the technical efficiencies of productions and the structures of the economies. The technical efficiencies effect is essential in accounting the responsibilities of inefficient productions (which is already included in the PBA but is missing in the CBA). On the other hand, the economic structure is important as it takes the effect of the extent of the imports and exports of an economic system into account. This is already included in the CBA but is missing in the PBA. A proper SBA approach should adequately consider both factors simultaneously. This could be done by either a technical adjustment made to the CBA or by structural considerations added to the PBA accounting.

Apart from the SBA methods distributing the emission burdens in proportion to the economic profitability of the trades for the producers and consumers, a group of the developed SBA methods has been proposed based on technical adjustments made to the CBA approach (e.g., Technology-adjusted CBA in (Kander et al., 2015)). A brief introduction to the developed SBA methods and their limitations in implementing them to climate policymaking are presented in *Supplementary Material 1*.

In the first proposal of SBA, Bastianoni et al. have proposed a Carbon Emission Added (CEA) approach for sharing the responsibilities among the producers and consumers (Bastianoni et al., 2004). The method, based on the Embodied Energy Analysis method (Odum, 2007), recommends the accumulation of the emission loads in the whole supply chain of production from the raw materials to the intermediate products and the final consumptions (Bastianoni et al., 2004). The cumulative emission loads are then normalized to fulfill the *Additivity* criterion of a proper allocation regime. Further details about the requirements for an appropriate carbon accounting method are presented in *Supplementary Material 2*.

The CEA method has been conceptually criticized due to the seemingly unfair allocation of the emission burdens to the end-users, even if they do not contribute to direct emissions, e.g., final distributors of a product in a supply chain (Csutora and Vetőné mózner, 2014). However, when considering the global trade system, such a case does not exist in a circular system of interconnected economies in which no part of the system is a sole producer or consumer. Even in the case that such a subsystem exists in the system under study, it usually plays a major role in the promotion of the consumption, and therefore is eligible for assuming responsibility (Lenzen, 2008). Moreover, the CEA has been criticized because of its sensitivity to the number of system components in the supply chain (Csutora and Vetőné mózner, 2014). This sensitivity is indeed problematic, while the choice of the level of aggregation changes the number of subsystems (Berzosa et al., 2014). However, while analyzing the global economy, the number of subsystems (countries) is fixed. Therefore, there would be no such sensitivity in the definition of the system and its components.

Based on the method proposed in (Bastianoni et al., 2004), the *CEA* of the *i*'th component of a (linear) system is equivalent to the normalized value of the summation of the direct emissions from the component (PBA_i) and the cumulative emission loads of the imported streams of type k from other system components j ($\sum\limits_{j\neq i}\sum\limits_{k}E_{ji.k}$) (Equation (1)).

$$\textit{From the production point of view}: \; CEA_i^* = PBA_i + \sum_{j\neq i}\sum_{k}E_{ji.k}$$

$$\textit{From the consumption point of view}: \; CEA_i^* = FCBA_i + \sum_{j\neq i}\sum_{k}E_{ij.k}$$

$$CEA_i = CEA_i^* \times \left(\sum_i PBA_i \Big/ \sum_i CEA_i^*\right) \tag{1}$$

Also, from the consumption point of view, the CEA is equivalent to the total carbon loads on the activities benefiting an economic entity, either from the consumption in the final demand or production sectors ($FCBA_i$) or by added-values from the export of the products and services k to destinations j ($\sum\sum E_{ij.k}$).

According to Equation (1), in the proposed CEA approach, the carbon load of any trade stream ($E_{ij.k}$) is assigned *equivalently* among the consumers of the final and middle products at different levels of the supply chain. In other words, in contrast to CBA, in the CEA, the desirability of the emissions and corresponding responsibilities are assigned for both the demand and supply sides. This is because of the fact that in the CEA, the emission loads on the exports are not excluded from the responsibilities of the producers. Also, the FCBA is a portion of the CEA, which is only attributed to the local consumption in the final demands, excluding the carbon loads on the exports. A further graphical description of how the CEA differs from the CBA is presented in *Supplementary Material 3*.

The CEA approach was proposed for a symbolic unidirectional supply chain in which only one product is produced and consumed among three components (Bastianoni et al., 2004). However, the idea has not been further developed nor applied to any regional or global case. This seems to be because of the fact that the application of the method requires the allocation of the emission loads on intermediate streams and local consumptions, which cannot become easily available for each product of each country in the global system. The main contribution of this paper is to overcome this shortcoming by proposing the notion that the *exergy cost* may be a valid proxy for apportioning the embodied emissions among different by-products of a subsystem.

The CEA requires no more data than the global trade data provided in the global trade yearbooks or aggregated Multiregional Input-Output (MRIO) tables. However, the application of the method is restricted to the development of an accounting technique for tracking the carbon load creation on both the intermediate and final demands as well as the trade streams. The proposed method in this research work is to use the exergy cost accounting formulation for allocating the total CEA of the country among final consumptions and exported streams of different products of a country. Hereafter, the proposed method is abbreviated as *CExA*.

In order to calculate the emission loads on the imported and exported streams, the emission balance equations (as in Equation (1) are formulated (Bastianoni et al., 2004). According to (Bastianoni et al., 2004), this could be done through an analogous approach to the Embodied Energy Costs in (Odum, 2007) or other thermodynamics-based methods for tracking the accumulation of the exergy destruction (Szargut and Morris, 1987) thermos-ecological cost (Szargut and Stanek, 2010), or exergoenvironmental costs within an energy system (Khajehpour et al., 2017). As the fossil-fuel related emissions account for almost 84% of the global CO_2 emissions (IPCC, 2014), only the energy-related CO_2 emissions have been considered in this study and the reference study for the CBA accounting presented in (Wiebe and Yamano, 2016). Therefore, the approach of the extended exergoenvironmental method has been applied to the calculation of the emission loads in this research work. This idea suggests the use of cumulative exergy destructions, rather than economic added-value production chain, as proxies for cumulative carbon emissions. The proportionality of the exergy destructions and embodied carbons on traded materials and services are discussed in the *Supplementary Material 4*.

According to the exergoenvironmental formulation (Meyer et al., 2009), Equation (2) presents the main carbon balance equation for each subsystem *i* (which are countries in the global system) having trades of goods and services from *k* different economic sectors with other *j* subsystems.

$$Y_i + \sum_{j\neq i}\sum_{k}E_{ji.k} = \sum_{j}\sum_{k}E_{ij.k} \tag{2}$$

In Equation (2), Y_i is the PBA of the subsystem i and $E_{ij,k}$ stands for the total embodied emission of product k exported from i to j. $E_{ij,k}$ is calculated according to Equation (3):

$$E_{ij.k} = e_{ij.k} \times V_{ij.k} \tag{3}$$

The variable $e_{ij,k,}$ is the specific cumulated carbon intensities (embodied emission per unit value of the product) and $V_{ij,k}$ is the amount (monetary or physical value) of product k produced in i and consumed in j. The specific cumulated carbon intensities $e_{ij,k}$ are identical for products of the same type k from the same producer i for all of the j destinations.

In case of the aggregation of some subsystems (e.g., the economic sectors of a country), according to the extended exergoenvironmental accounting (Khajehpour et al., 2017), the total emission loads are to be distributed among different types of outputs (k and l) in proportion to their cumulative exergetic costs (Equation (4)):

$$E_{ij.k} \Big/ ExC_{ij.k} = E_{ij.l} \Big/ ExC_{ij.l} \tag{4}$$

In Equation (4), the $ExC_{ij,k}$ is the cumulative exergy destruction of product k, which is traded from country i to country j. Combining Equations (3) and (4) gives:

$$e_{ij.k} \Big/ e_{ij.l} = \left(ExC_{ij.k} \Big/ V_{ij\cdot k} \right) \Big/ \left(ExC_{ij.l} \Big/ V_{ij\cdot l} \right) \tag{5}$$

The values of the unit exergy costs of products produced in i $(ExC_{ij.k} / V_{ij.k})$ are different for every economic activity k. However, due to lack of country-specific sectoral exergy cost accounting results, the ratio of unit exergy cost of product k to unit exergy cost of product l $(ExC_{ij.k} / V_{ij.k})/(ExC_{ij.l} / V_{ij.l})$ are assumed to be the same for all subsystems i. For instance, the ratio of unit exergy cost of textile production (k) to unit exergy cost of cement production (l) are assumed to be identical in all of the modeled countries (i). These values are calculated from national exergetic input-output analysis research by Rocco (2016), and the results are used in this modeling.

Assuming the validity of this proxy, the detailed import data of any sector of a country could be aggregated into an overall import profile of the country, no matter how it is distributed among the economic activities of the country. Although this aggregation may introduce some uncertainties in the exergy cost accounting of the aggregated economic sectors, it reduces the amount of the required data by 97% and hence improves the applicability of the accounting method for the countries for which the detailed data of the MRIO are not available. This uncertainty in the use of the exergy cost proxy is a manageable source of uncertainty and, therefore, could be reduced in further detailed accountings.

The novelty of this research work is that a new approach for accounting the emission loads on the materials and services is proposed, which is based on the proportionality of the cumulative exergy costs and the embodied emissions. As a result, the CExA responsibility allocation method may be applied for accounting the shared emission inventories in the global system. Considering the fairness of the CExA approach in accounting for the upstream and downstream responsibilities in an equal manner, the sharing method may better reflect the policy implications of the national inventories.

3. Results and discussion

3.1. Data source for CBA and CExA accounting

For the sake of comparability of the results with a reference CBA inventory, the trade data according to the 2016 edition of the Intercountry Input-Output (ICIO_2016) is used (Wiebe and Yamano, 2016). The OECD developed the ICIO_2016 database. Accordingly, the CExA emission inventories are calculated for 62 countries plus a 63rd subsystem representing the rest of the world. The latter aggregates the trade data for 177 less developed countries of the world, for which the individual MRIO tables are not available. Also, based on the third revision of the International Standard Industrial Classification of All Economic Activities (ISIC Rev.3) the economic activities are categorized into 34 sectors. ICIO_2016 database allows tracking carbon inventories before and after the Kyoto protocol. This is important as the Kyoto protocol and its mandates are understood as the main reasons for the outsource of emissive industries to the developing world, which has resulted in the carbon leakage effect (Aichele and Felbermayr, 2015). The comparison of CBA, PBA, and CExA is especially helpful in tracking the temporal changes before and after the Kyoto protocol in developed and developing countries. Considering the data availability from the ICIO_2016, the CExA of the countries is calculated from 1995 through 2011.

3.2. Comparison of CExA results with PBA and CBA

Fig. 1 presents the CExA per capita of the countries for the year 2011.

The global average value of the CExA per-capita is 3.4 t CO_2 (equivalent to those of CBA and PBA) while the average values of the developed and the developing countries are 10.8 and 2.9 t $CO_{2,}$ respectively. Table 1 compares the carbon emission per capita in the developed and developing countries for different allocation approaches.

According to Table 1, the averaged CBA and PBA per-capita are 11.1 and 9.8 t CO_2 for the developed countries and 2.8 and 3.1 for the developing countries (calculated from the results of Wiebe and Yamano (2016)). The last column of Table 1 shows higher shares of the imported carbon loads for the developed economies than the developing countries. This is a result of the carbon leakage phenomenon. Also, Table 1 shows that, in an overall view, the CExA shares the responsibilities among producers (in the developing countries) and the consumers (in the developed countries). This is according to the expectation from an SBA. Further detailed numeric values of the calculated shared emission inventories of the CExA are presented in tabular and scatter-plot forms in the *Supplementary Material 6*. Also, Fig. 2 shows the changes in the carbon inventories according to the CExA as a percentage change from the PBA and CBA.

In contrast to the CBA, the expectations referring to the SBA emission inventories are not systematically supporting the conventional categorization of the countries into developed (OECD) and developing (non-OECD) countries (Kander et al., 2015). This is due to the fact that the countries within each one of these groups differ from each other according to two important aspects of climate responsibility: their economic structure and the carbon intensities of their economic activities. The economic structure is important because it refers to the relative extent of the demand for international trade in the entire economy. Also, the carbon intensities of products incorporate the technical efficiencies of producers in carbon accounting of the traded streams and, therefore, should be accounted for in a fair climate inventory regime.

3.3. Effect of the economic structures on CExA

According to the product portfolio of the economic sectors, the average carbon (direct and indirect) intensity of the countries is calculated and depicted in Fig. 3 below.

According to Fig. 3, on average, the direct emissions account for 80.4% of the countries' emissions while the rest are the emission

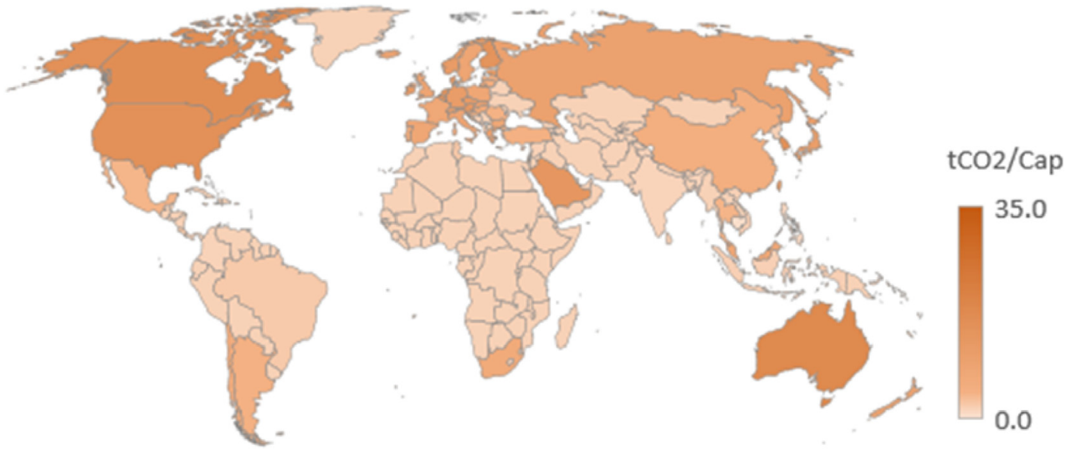

Fig. 1. World map of the distribution of the CExA per-capita of the countries in 2011.

Table 1
Comparison of the CO_2 emission per capita in 2011 according to different accounting approaches.

CO_2 emission per capita per year (tCO_2/ca.yr)	PBA	CBA	CExA	Share of indirect emissions in total carbon load (%)
Developed countries	9.8	11.1	10.8	38.8%
Developing countries	3.1	2.8	2.9	28.9%
Global average	3.4	3.4	3.4	19.6%[a]

[a] This is for the global average among all 198 countries. The average share of the imported carbon to the total carbon load among the 62 studied countries is 34.4%.

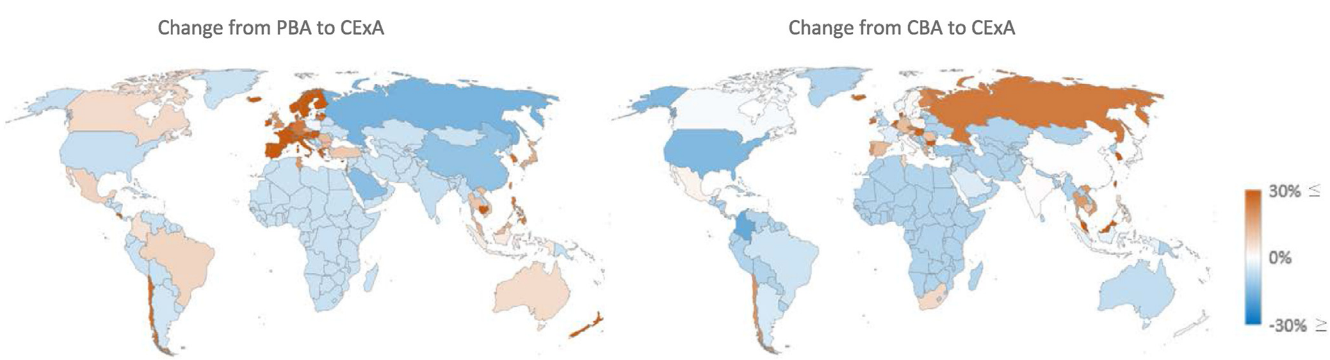

Fig. 2. Changes from the PBA (left) and the CBA (right diagram) to the CExA sharing approach of this study.

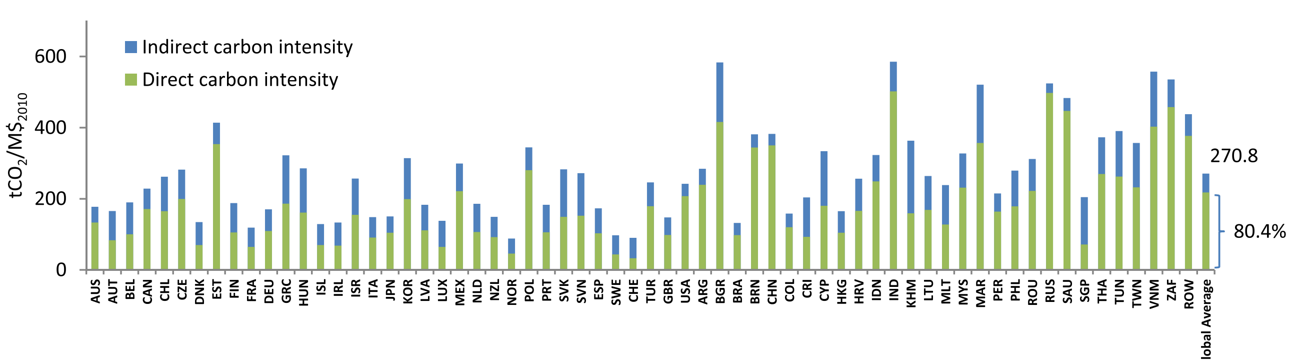

Fig. 3. Total carbon intensities of the economies and the shares of the direct and indirect carbons for the modeled economies.

loads on the imported products. This share is as high as 92% for major developing countries (e.g., China, India, and Russia) while it as low as 50% for import-oriented countries (e.g., Singapore, Austria, Belgium).

In order to better analyze the effect of sharing, the countries of the world are categorized based on the economic structure and emission intensity criteria. The developed economies (OECD) are categorized into three groups: USA (less importing), “other G7″ countries (Canada, France, Germany, Italy, Japan, United Kingdom), and “the rest of the OECD” countries. The “other G7″ group of countries are cleaner producers while importing more than the USA and less than the other OECD countries. In contrast, “the rest of the OECD” group of countries are more net importers among the developed economies. On the other hand, the less carbon-efficient countries in the developing world are categorized into China (major producer and exporter), “BRIIS” countries (Brazil, Russia, India, Indonesia, South Africa) and a group of the rest of the world countries. The BRIIS group of countries are major developing countries with higher carbon intensities than China and fewer imports.

Also, to interpret the effect of the economic factors causing different carbon inventories, some facts and figures referring to the economic and exergetic indicators of the modeled countries in this research work are presented in Supplementary Material 5. Fig. 4 depicts the relative climate-economic characteristics of the mentioned groups of countries. The economic structure of the countries (in terms of the ratio of imported (indirect) carbon to the direct emissions) and their production efficiency (in terms of their carbon intensities of national gross domestic products in kgCO2/$\$_{2010}$) are analyzed for the 6 categories to help understand the behavior of CExA (Fig. 4).

Based on the data presented in Figs. 3 and 4, the carbon intensity of the developed (developing) countries is normally lower (higher) than the global average of 0.22 $kgCO_2/\$_{2010}$. More specific to the economic structure of the country groups in this study, the average carbon intensity of the other G7 has the smallest value in the chart and, after other OECD, the second-largest share of indirect to direct emissions. This clearly shows the effect of carbon leakage for outsourcing polluting industries from these countries. More import-dependent OECD economies (e.g., Luxembourg (LUX), Sweden (SWE), and Switzerland (CHE)), as well as the less productive developing economies (e.g., Costa Rica (CRI), Cambodia (KHM), Singapore (SGP)), have the highest shares of the imported emissions. Also, a further comparison of the economic structures of the countries clarifies how the countries are different according to the most productive sector of their economies. For instance, among the major developing countries, Brazil (because of its high share of bio-fuel production), India (as the least carbon-efficient economy (see Fig. 3)), and Saudi Arabia (because of its fossil-fuel-based economy) show different levels and compositions of the carbon intensities. Oil-reliant economies have very low shares of indirect carbon loads for their consumptions. Therefore, they experience the same CExA-based carbon inventory relative to PBA and CBA. This relatively low share of the imported carbon is because of the fact that the crude oil production industry, as the main motivator of the economy, is itself a very energy (and carbon) intensive industry which leads to high PBA, while the main imports to these countries are associated with less carbon-intensive products imported to cover the final demands and not for intermediate processing productions.

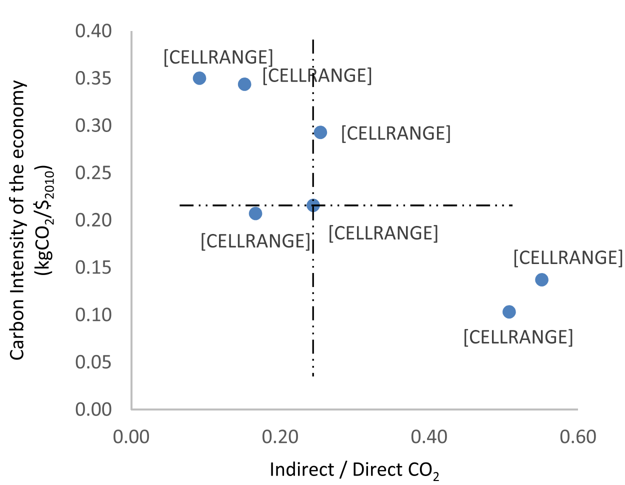

Fig. 4. Comparison of the economic structure and the production efficiencies of the country groups.

Fig. 5 shows the values of the CExA and (the shares of indirect emission loads) in comparison to the PBA and CBA accounting results (calculated from the results presented in (Wiebe and Yamano, 2016)) for the mentioned 6 categories.

Furthermore, along with the changes in the production levels, economic structures, and the production efficiencies, the accounted CExA of different countries experience gradual changes in time. Fig. 6 shows the temporal changes of the accounted inventories as well as the PBA and CBA of the above group of countries (from the reference study (Wiebe and Yamano, 2016)).

3.4. Temporal changes of the CExA

The relative behavior of the CBA and PBA inventories of the countries has been intensively studied in the literature (Davis and Caldeira, 2010; Davis et al., 2011; Wiebe and Yamano, 2016) and is not further discussed here. The stable proportionality of the SBA to the PBA and CBA through time shows that there have been no major structural shifts in the relative production and consumption behavior of the countries. However, according to the changes in the production levels and the efficiency improvements, there have been gradual increases (decreases) in the shares of the carbon inventories of developing (developed) countries (Fig. 6).

Taking further “underlying stories” into account reveals the differences between the subcategories in the developed and developing countries (Kander et al., 2015). For instance, the relative imported carbon to the direct emissions of the USA is 16.7%, the smallest number among the OECD countries, while the average values for the OECD and non-OECD countries are 37.4% and 15.4%, respectively (Fig. 4). Therefore, although the CBA of the developed countries is more than their PBA (due to the carbon leakage effect), different shares of the imports in the total consumption of these countries cause different CExA behaviors. Thus, the CExA inventory of the United States, as the most self-sufficient economy among all developed countries, has always been less than its PBA. This is because of its high PBA in place and the lower share of the demand for import of the embodied carbons, relative to the size of its productions and direct emissions of the USA (Figs. 4 and 5). In other words, relative to its high production-based emissions, while considering the total carbon trades for both the intermediate industrial productions and final consumptions, the USA is adequately charged for their high PBA and, therefore, have a lower responsibility for the global trade of the embodied carbons.

However, the increasing demand for the embodied carbon of imports for the other G7 countries increases the CExA of these countries almost to their CBA. The lower productivity of the high-consuming other OECD countries causes the highest share of the demand for indirect carbons and therefore places their CExA higher than their CBA.

On the other hand, in the developing world, the different ratios of dependence on the imported carbons cause different CExA-

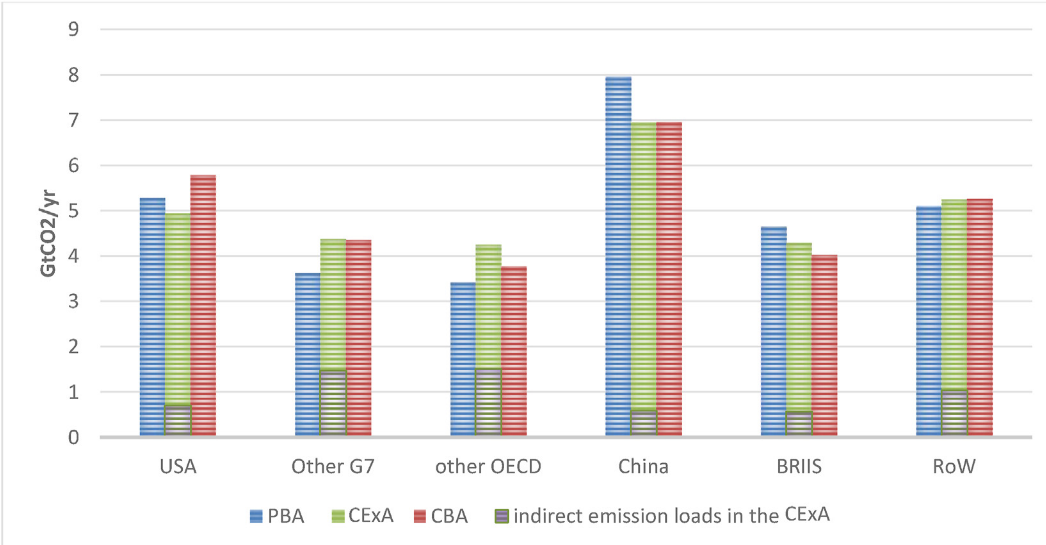

Fig. 5. Comparison of the CExA carbon accounting with the PBA and CBA approaches in 2011.

based carbon inventories. Similar to the developed countries, the higher the share of the imported carbon in total consumptions in industries and final consumers, the higher the CExA. Therefore, for China, the CExA is almost as low as the CBA, while it increases more than the CBA for the BRIIS group of countries.

Finally, a clear relationship between the behavior of carbon inventories has been experienced. For instance, a dramatic increase in the consumption of goods and services for both the final demands and the intermediate productions in the developed countries, have resulted in a dramatic decrease in the consumption of the low and medium-income developing countries ("Rest of the World") in the year 2000 (Fig. 6). Detailed investigations of the changes in the global trades of different products and among different regions, clarify the underlying factors causing such changes. Therefore, further analyses of individual countries are available from the results presented in Supplementary Material 6.

4. Conclusions

Tackling climate change needs integrated will and action in the global community. In an ideal case, the differentiated responsibilities of countries should consider different aspects of climate equity. This paper proposes a carbon accounting method for a proper allocation of carbon loads among the countries. This can help in an accurate accounting of the equity aspects of emission responsibilities.

A fair allocation of the contributions of individual countries to the global carbon emissions necessitates effective consideration of the causes of emissions in both the demand and supply. Therefore, from the production point of view, the producers shall be responsible for both the extent of their production activities and the technical efficiency of their productions. Whereas, simultaneously, from the consumption point of view, economies should take the responsibility of the extent and the source of their consumptions in both the final demands of their country (e.g., residential and transportation) and the intermediate consumptions at the local economic activities. This comprehensiveness guarantees the maximum effectiveness of the climate policies by motivating both the producers and consumers toward lower emissions.

In this research work, by combining the rational of the CEA and the extended exergoenvironmental method, a new SBA approach is developed and applied to the global system. The CExA approach satisfies the fairness criteria and recommends a holistic view for accounting the global responsibilities related to the GHG emissions. It incorporates the functionalities of both the PBA and CBA principles. Therefore, it can account for levels and qualities of productions as well as the levels and choice of the sources of the imports for the total consumptions in both the final demands and intermediate industries. Consequently, while considering the CExA carbon inventories, the countries are motivated toward reducing their direct emissions (by less and greener productions) and the indirect emission loads on the imports (by lower total consumptions and choice of greener sources for imports), at the same time.

With the aid of exergy cost accounting for the allocation of the carbon emissions among the multi-products of each component of the global system, the CExA approach is applied to track the carbon loads on the traded streams. As a result, the CExA approach recommends a fair SBA allocation of the carbon responsibilities among the countries.

In summary, according to the accounting results presented here, there are two features in the CExA:

First, sharing is not equivalent to averaging: the SBA inventories do not necessarily lie between the PBA and CBA as they are not averaging the conventional inventories; instead, they are incorporating further economic and technical details in the accounting.

Second, in contrast to the CBA and PBA inventories, there are no systematic benefits expected for the developed or developing groups of countries. This is because both the technical efficiencies and the economic structures of countries matter in a proper SBA accounting. Therefore, considering the differences in these two characteristics, there are different relative SBA inventories among the countries in both groups.

Nevertheless, the method proposed here accounts for the induced consumption in the producing country by direct consideration of the PBA as an inherent part of the SBA. Therefore, the CExA approach of this research work is valid for full consideration of the differences in the region-specific technical efficiencies and emission factors as they are inherently incorporated in the PBA part of the proposed SBA inventory.

As in any accounting method, there would be some losers and winners under the non-PBA accounting rules. For instance, our results show that, according to the proposed sharing approach, the

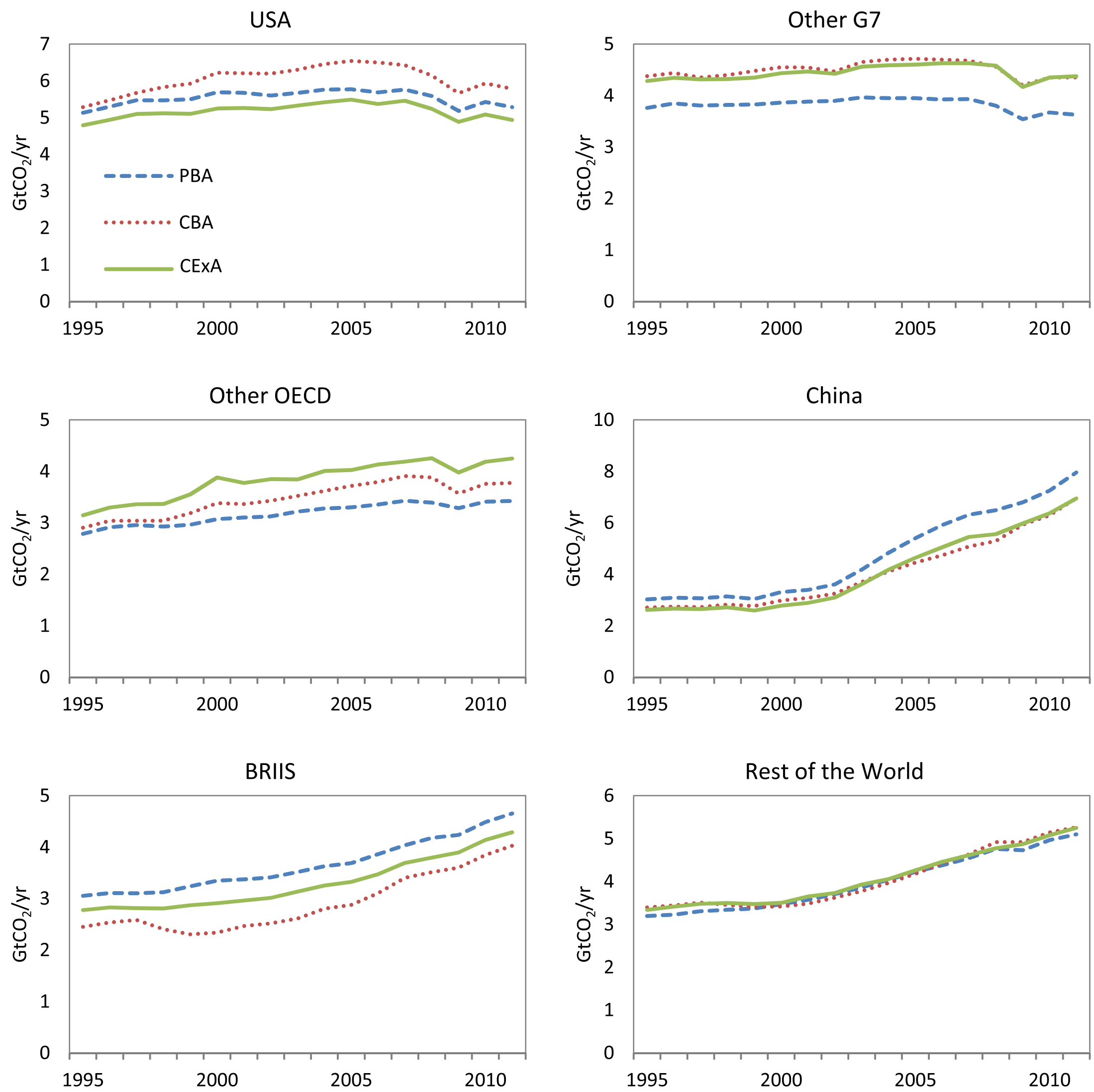

Fig. 6. Temporal changes in the carbon inventories in different accounting approaches. The legends are similar for all graphs.

group of the developed countries which have benefitted the most from the *carbon leakage* effect by outsourcing the polluting industries to the developed nations, are found to be relatively most penalized for the embodied emissions on the imports to their economy.

The holistic consideration of different responsibility-generating factors in both the supply and demand sides, which is present in the proposed accounting method in this research work, is an advantage over the other approaches. The rationality of the method can overcome resistance against its applicability in sharing the contributions in integrated global climate action.

Indeed, all accounting methods have limitations for the design and implementation of climate policies. The SBA methods are developed to improve the effectiveness of conventional accounting methods. However, they cannot include many climate equity considerations and the "indirect and dynamic" effects of global climate policies (Kander et al., 2015). This necessitates, for example, the incorporation of SBA accountings into the climate dynamic models in future studies. Data on inter-country input-output tables is improving by covering a higher number of countries and for more recent years. Also, the developed CExA method should be applied to more comprehensive and updated ICIO tables in the future.

CRediT author statement

Hossein Khajehpour: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Yadollah Saboohi:** Funding acquisition, Project administration, Conceptualization, Methodology, Resources, Supervision. **George Tsatsaronis:** Funding acquisition, Project administration, Conceptualization, Methodology, Resources, Supervision, Validation, Review and editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124438.

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