Journal of Cleaner Production 234 (2019) 1399–1420

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Analyzing CO_2 emissions flows in the world economy using Global Emission Chains and Global Emission Trees

Luca Fraccascia [a, b, *], Ilaria Giannoccaro [c]

[a] Department of Computer, Control, and Management Engineering "Antonio Ruberti", Sapienza University of Rome, via Ariosto 25, 00185, Rome, Italy
[b] Department of Industrial Engineering and Business Information Systems, University of Twente, Drienerlolaan 5, 7522, NB, Enschede, the Netherlands
[c] Department of Mechanics, Mathematics, and Management, Polytechnic University of Bari, Viale Japigia 182, 70126, Bari, Italy

ARTICLE INFO

Article history:
Received 29 December 2018
Received in revised form
25 June 2019
Accepted 26 June 2019
Available online 27 June 2019

Handling editor: Kathleen Aviso

Keywords:
CO2 emissions
Global supply chains
Multi-regional inputoutput analysis
Global Emission Chains
Global Emission Trees

ABSTRACT

Because of the increasing international trade, monitoring tools are required that quantify and analyze CO_2 emissions at a global level. This paper contributes to this literature by adopting a consumer-oriented approach and using two tools based on Multi-Regional Input-Output tables, i.e., the Global Emissions Chains (GECs) and the Global Emissions Trees (GETs). The GEC is proposed with an industry-level perspective so as to provide detailed information about the extent to which the final demand of an industry of a country drives indirect CO_2 emissions by any industry of any other country. The GET is defined as a simplified graphical structure of the GEC, which includes only the industries providing the highest contribution of CO_2 emissions. The tools are described and new indices are developed with the aim of conducting multiple analyses with different purposes. Applications are given with specific emphasis to the different analyses that can be carried out. In particular, the GEC and the GET of a specific Italian industry are presented and comparisons with GECs and GETs of different countries are discussed. How to use the tools to develop more effective decarbonization strategies at both country and global levels is also described.

1. Introduction

Actually, CO_2 emissions are recognized as the main anthropogenic cause of global warming (IPCC, 2014) and reducing these emissions is now one of the greatest issues in the globalization context. Nevertheless, after the approval of the Kyoto Protocol, which was aimed at fighting global warming by reducing greenhouse gas concentrations in the atmosphere to "*a level that would prevent dangerous anthropogenic interference with the climate system*" (UNFCCC, 1997), there has been no reduction in CO_2 emissions at the global level (e.g., Fernández-Amador et al., 2017). Conversely, the global CO_2 emissions have grown by 45% since 2000, to an extent never seen before (The World Bank, 2017; United Nations, 2017). A 66% chance of limiting global warming to 2 °C by 2100 (which is the main goal of the Paris climate agreement) implies that global CO_2 emissions must decline to 24 $GtCO_2$/year by 2030, 14 $GtCO_2$/year by 2040, and 5 $GtCO_2$/year by 2050 (Rogelj et al., 2016). In line with this stream, the European Union (EU) Energy Roadmap requires that each EU country will cut the CO_2 emissions produced within its national borders to 40% below 1990 levels by 2030, to 60% by 2040, and to 80% by 2050 (European Commission, 2011).

To pursue the aim of reducing overall CO_2 emissions, it is fundamental analyzing CO_2 emissions at the global level. Because of international trade, in fact, CO_2 emissions flow among countries traversing the geographical borders. In particular, CO_2 emissions due to international trade occur because the consumption of a generic product in a generic country leads to CO_2 emissions in the other countries that are involved in its production network (global supply chain). As a consequence, in each country not only the domestic consumption but also the foreign demand is accountable to generate CO_2 emissions. Similarly, each country contributes to CO_2 emissions at the global level with emissions generated both within the country (internal) and in other countries (external). Recent studies analyzing CO_2 emissions have found that the amount of CO_2 embodied in international trade has grown from 5.3 Gt in 2001 (Peters and Hertwich, 2008) to 8.1 Gt in the 2008–2012 period (Caro et al., 2017). Thus, neglecting this aspect leads to

* Corresponding author. Department of Computer, Control, and Management Engineering "Antonio Ruberti", Sapienza University of Rome, via Ariosto 25, 00185, Rome, Italy.
E-mail address: luca.fraccascia@uniroma1.it (L. Fraccascia).

https://doi.org/10.1016/j.jclepro.2019.06.297
0959-6526/

misunderstanding the contribution of each country to CO_2 emissions at the global level, as well as impedes to formulate effective decarbonization strategies at national and global levels.

To overcome these limitations, proper accounting tools are needed, which analyze CO_2 emissions at the global level. A common approach is attributing the responsibility of CO_2 emissions to the 'final demand' sectors (i.e., following a consumer-oriented perspective). In this regards, alternative tools are the environmentally extended Multi-Regional Input-Output (MRIO) analysis (Lenzen et al., 2013; Tukker et al., 2009; Wiedmann, 2009; Wiedmann et al., 2007) and the National Carbon Intensity (NCI) method (Caro et al., 2017, 2014). These tools enable the identification of consumer-based emission responsibility, investigating in detail the emissions embodied in flows of goods/services on the basis of sector at the global level.

Despite these tools are developed to track global CO_2 emissions flows among countries by taking into account the role of global supply chains, they have been mainly used to provide aggregate information concerning CO_2 emissions of a country as a whole or a global sector, selected as accounting units. In fact, their final aim is to identify the countries that are main exporters or main importers of CO_2 emissions. However, in order to support policymakers in designing effective CO_2 reduction strategies at national and global levels, more detailed information concerning the role of each specific industry of a country in the CO_2 production at the global level is needed. This requires to propose CO_2 accounting tools with a focus on the single industries of a country as accounting unit. In other words, this means to highlight the extent to which the final demand of a given industry of a country drives CO_2 emissions by other domestic and foreign industries, because of their involvement in the global supply chains.

This paper is aimed at fulfilling these requirements by employing two tools, based on the MRIO analysis (Miller and Blair, 2009): (1) the Global Emission Chains (GECs) and (2) the Global Emission Trees (GETs). In particular, it is proposed a new application with a focus on the single industries of a country. Furthermore, new indices are developed, based on GECs and GETs, useful to conduct multiple analyses and to drive the national and international decarbonization strategies so as to be more effective.

First, the paper offers a detailed description of how to compute the GECs at the industry level. The GEC of the generic *j*-th industry of the *k*-th country highlights how much CO_2 is produced by each of the industries of the world economy for each dollar of final demand of industry *j* of country *k*. In this way, the tool provides very detailed information about the effect of the production of a given industry in terms of CO_2 emissions at the global level. The GEC can support analyses at a higher level of aggregation, mainly distinguishing between direct vs. indirect and domestic vs. foreign CO_2 emissions. Therefore, specific indices are defined to compare different industries of the same country, the same industry in different countries, and the same industry over time.

Then, the paper describes the GETs. Because of the high number of the involved industries in the global production networks, graphically showing GECs of a generic industry of a country could be a hard task, so that the interpretative power of the tool could be reduced. To overcome this problem, the GET of the generic *j*-th industry of the *k*-th country can be used. It graphically depicts a simplified structure of its GEC, keeping only the most essential CO_2 emission contribution relationships for the root industry. In particular, GETs highlight the industries of the world economy mainly contributing to generate CO_2 emissions for each dollar of final demand of the root node, so graphically showing the interdependencies among industries involved in global supply chains. This is relevant and effective information almost neglected in previous tools. To develop GETs, the procedure suggested by Zhu et al. (2015) to develop the global value trees from the global value chains is followed. Therefore, even though GETs are a simplified version of GECs, they can be considered a new tool in the context of CO_2 emissions. To analyze GETs and provide additional useful information for policymakers interested in developing decarbonization strategies, specific indices are also developed. They assist in identifying the sectors that contribute at most to CO_2 emissions at national and global level in an easy manner.

The paper is structured as follows. Section 2 presents a brief literature background on the papers that study CO_2 emissions at the global level. Section 3 presents the methodology to build GECs and GETs. Section 4 discusses some applications of the proposed tools. Finally, the paper ends with discussion and conclusions (Section 5).

2. Literature background

There is an extensive literature that studies CO_2 emissions from different perspectives. Several studies are aimed at highlighting the main drivers for the recent growth in global CO_2 emissions. For example, Arto and Dietzenbacher (2014) find that this rise was driven by the population growth and the increase in per capita consumptions, despite a moderator effect played by the reduction in the global emission intensity (i.e., the amount of CO_2 emitted per unit of economic output produced at the world level). In this regard, Malik et al. (2016) point out that, despite the global emission intensity decreased over time, the effect of this reduction has been not strong enough to hinder the effects of increasing population and per capita consumptions. These studies also find that global emission intensity decreased mainly because countries reduced their national emission intensity, i.e., the amount of CO_2 emitted in atmosphere per unit of GDP, thanks to advances in technology towards higher energy efficiency (Dong et al., 2018; Yan et al., 2018) and changes in fuel mix towards a higher share of renewable energy sources (Mohlin et al., 2018). These results are supported by other studies conducted on single national economies (e.g., Liu et al., 2019), for example China (Z. Wang et al., 2019b; Yan et al., 2018), India (Zhu et al., 2018), and Sweden (Schmidt et al., 2019). However, recently it has been highlighted that reductions in global emission intensity have been hampered by the growing international trade, because of the transfer of production from advanced economies to emerging economies, where production is relatively more emission-intensive (Wang et al., 2017). In fact, with the aim to reduce the amount of CO_2 produced within the national borders, many countries have delocalized high-carbon industrial activities in other countries (Springmann, 2014; Z. Wang et al., 2019a). In this regard, several studies have been conducted with the aim to assess the CO_2 emissions flows embodied in international trade (e.g., Caro et al., 2017; de Vries and Ferrarini, 2017; Duan and Jiang, 2018; Meng et al., 2018). These studies differ among them for the set of the countries considered, the data sources (e.g., different IO databases), the specific methodology adopted, and the time period taken into account for the analysis. However, they use a similar approach. In particular, they compute for each country: (1) the amount of CO_2 produced due to domestic consumption, i.e., generated within the national borders to produce outputs sold on the national markets; (2) the amount of CO_2 virtually exported by the country, i.e., generated within the national borders to produce outputs sold abroad; and (3) the amount of CO_2 virtually imported by the country, i.e., generated abroad to produce outputs sold on the national markets. These studies highlight that, despite delocalizing industrial activities in other countries is an effective strategy to reduce the CO_2 emissions at the national level, this practice might be responsible for increasing the CO_2 emissions at the global level, *ceteris paribus*, since the same industry in different countries may be characterized by different amounts of CO_2 generated per unit of output. For instance, according to Xu et al. (2017), for each dollar of output of "Coke, refined petroleum, and nuclear fuel" industry, the USA produce 0.394 Kg of CO_2 whilst China produces 5.1 Kg of CO_2. In this regard, Jiang and Green (2017) demonstrate that changing the global supply chain geography towards China positively contributed to 919 Mt CO_2 equivalents to global GHG emissions annually in the period 2001–2008.

In these foregoing studies, there are two main limitations. First, CO_2 flows among countries are analyzed without identifying the specific industries responsible for these international flows. Since this is relevant information, some studies have recently tried to address this issue, even though without providing an extensive analysis. For example, Zhang et al. (2019) assess the backward and forward CO_2 emission linkages focusing on the global construction industry, i.e., the amount of CO_2 produced by industries upstream of the production chains and the amount of CO_2 virtually exported to industries downstream of the production chains. Wang et al. (2019) analyze the CO_2 flows at the industry level but only between two countries, i.e., China and Australia. A second limitation of the above-mentioned studies is that they mainly consider the overall amount CO_2 produced without providing specific indices analyzing decarbonization trends, i.e., the reduction of the CO_2 emissions intensity over time.

GECs and GETs are proposed in the next so as to overcome both these limitations.

3. Methods

This Section is divided into three subsections. Section 3.1 describes MRIO tables. Section 3.2 presents the GECs. Finally, Section 3.3 introduces the GETs.

3.1. Multi-Regional Input-Output tables

This Section introduces MRIO tables, following the traditional Input-Output methodology (Miller and Blair, 2009).

In this paper, the MRIO tables provided by the World Input-Output Database (WIOD), Release 2013 (Timmer et al., 2015) are used. These tables cover 35 industries for each of the 40 national economies plus the rest of the world (RoW) for the years from 1995 to 2011 (see the Appendix for the list of industries and the list of countries considered). For each year, there is a harmonized global level input-output table recording the input-output relationships between any pair of industries in any pair of economies. The numbers in these tables are in current basic (producers') prices and are expressed in millions of US dollars. Table 1 shows an example of a global MRIO table with two countries, each of them having two industries.

Each row and each column denote an industry of a national economy. The last row and the last column (highlighted in red in Table 1) record the total industry output and its 4×1 vector is denoted by x. Hence, the generic element x_i denotes the total output generated by industry i. This output is in part destined to be absorbed by other industries and in part destined to satisfy a final demand. In this regard, the 4×4 inter-industry table (highlighted in green in Table 1) is called "transactions matrix" and is denoted by Z. The generic element Z_{ij} denotes the output of industry i that is transferred to industry j. Besides intermediate industry use, the remaining outputs are absorbed by the final demand (highlighted in blue in Table 1), which mainly includes household consumption and government expenditure. In Table 1, only the aggregated final demand for the two national economies is displayed. The 4×1 vector of final demand is denoted by f and the generic element f_i denotes the final demand observed by industry i. Hence, for the generic industry i, it follows that:

$$x_i = \sum_{j=1}^{4} Z_{ij} + f_i \tag{1}$$

Finally, the penultimate row of the matrix denotes the value added generated by each industry. The 4×1 vector of value added is denoted as v and the generic element v_i denotes the value added generated by industry i.

Consider a generic input-output table where n industries of c countries are considered. For the overall table, it follows that:

$$x = Z \cdot i + f \tag{2}$$

where i is the so-called "summation vector", i.e., the $(n \times c) \times 1$ vector with all elements equal to one. The matrix Z and vector x can be used to compute the "matrix of the technical coefficients" (A), as results from the following equation:

$$A = Z \cdot \hat{x}^{-1} \tag{3}$$

where the "hat" is used to denote a square matrix so that $\hat{x}_{ii} = x_i \ \forall \ i = 1 \ldots (n \times c)$ and $\hat{x}_{ij} = 0 \ \forall \ i \neq j$. The generic element A_{ij} denotes the monetary flow transferred from industry i to industry j for per each unit of output produced by industry j. Hence, Equation (2) can be rearranged as:

$$x = A \cdot x + f = (I - A)^{-1} \cdot f = L \cdot f \tag{4}$$

where I is the $(n \times c) \times (n \times c)$ identity matrix so that $I_{ii} = 1 \ \forall \ i = 1 \ldots (n \times c)$ and $I_{ij} = 0 \ \forall \ i \neq j$. The matrix $(I - A)^{-1}$ is often denoted as L and is called the "Leontief Inverse" (Leontief, 1986). The generic element L_{ij} denotes the output produced by industry i per each unit of final demand of industry j.

Table 1
Input-output table for a simplified world economy made by two countries, each of them having two industries.

		country 1		country 2		final demand		total output
		industry 1	industry 2	industry 1	industry 2	country 1	country 2	
country 1	industry 1	50	30	30	5	30	10	155
	industry 2	15	90	15	50	25	20	215
country 2	industry 1	40	10	100	30	10	50	240
	industry 2	40	50	90	80	40	90	390
value added		10	35	5	225			
total output		155	215	240	390			

3.2. The Global Emission Chains

The GEC of the *j*-th industry of the *k*-th country is proposed as a tool highlighting how much CO_2 is produced by any industry of the world economy for each dollar of final demand of industry *j* of country *k*, because of its global supply chain.

In order to build the GECs, data on the amount of CO_2 emitted per unit of output of each industry of each country are required. In this regard, the WIOD includes data on the total amount of CO_2 generated by each industry of each country for each year between 2000 and 2009. Let e^p be the $n \times 1$ vector whose generic element ${e^p}_s$ denotes the total amount of CO_2 emission generated by industry *s* of country *p*. First, the $(n \times c) \times 1$ vector of CO_2 emissions generated by each industry of each country is built. This vector is denoted as *e*:

$$e = \begin{bmatrix} e^1 \\ e^2 \\ \dots \\ e^c \end{bmatrix}$$

Then, the vector *ei* is computed by the following equation:

$$ei = \hat{x}^{-1} \cdot e \quad (5)$$

where the generic element $ei_{(k-1)\times n+j}$ denotes the amount of CO_2 generated by industry *j* of country *k* for each unit of output produced.

Finally, the $(n \times c) \times (n \times c)$ GECs matrix (denoted by M) is computed as follows:

$$M = \widehat{ei} \cdot L \quad (6)$$

where the "hat" is used to denote a square matrix so that $\widehat{ei}_{ss} = ei_s \ \forall \ s = 1\dots(n \times c) \times (n \times c)$ and $\widehat{ei}_{sr} = 0 \ \forall \ s \neq r$. Here, the generic element $M_{(k-1)\times n+j,(k-1)\times n+j}$ indicates the amount of CO_2 directly produced by the *j*-th industry of the *k*-th country per dollar of final demand and the generic element $M_{(m-1)\times n+i,(k-1)\times n+j}$ indicates the amount of CO_2 produced by the *i*-th industry of the *m*-th country per dollar of final demand of the *j*-th industry of the *k*-th country. As a result, the column *(k-1)* $\times$ *n* + *j* of the *M* matrix is the GEC of the *j*-th industry of the *k*-th country.

As an example, a part of the M matrix computed for 2009 is shown in Table 2 (the overall matrix is provided as supplementary material). This matrix shows that the "Pulp, Paper, Printing and Publishing" industry in France directly produces 0.0635 Kg of CO_2 per dollar of final demand. Furthermore, it indicates that for each dollar of final demand of this industry, for example 0.0015 kg of CO_2 are generated by the "Chemicals and Chemical Products" industry in France and 0.0000595 Kg of CO_2 are generated by the "Mining and Quarrying" industry in Australia.

GECs work under the assumption that all the products generated by one industry have the same CO_2 emission intensity. Such an assumption is due to the lack of input-output tables for specific products and is also adopted by other studies (e.g., Caro et al., 2017; de Vries and Ferrarini, 2017).

The GEC of the *j*-th industry of the *k*-th country can be analyzed by using the following indices:

- the *direct CO_2 intensity*, i.e., the amount of CO_2 directly produced by the *j*-th industry of country *k* for each dollar of final demand;
- the *domestic CO_2 intensity*, i.e., the CO_2 produced directly and indirectly within the national borders of the *k*-th country for per each dollar of final demand of its industry *j*;
- the *foreign CO_2 intensity*, i.e., the CO_2 produced by foreign industries per each dollar of final demand of industry *j* of country *k*;
- the *overall CO_2 intensity*, i.e., the amount of CO_2 generated along the overall chain (i.e., all the world industries) per each dollar of final demand of industry *j* of country *k*.

These indices precisely quantify the CO_2 emissions produced for per each dollar of final demand of industry *j* of country *k* distinguishing between the emissions generated by the industry itself (*direct*), the emissions generated by the industry itself and the local industries connected in the local production networks (*domestic*), and the emissions produced by the industries connected in the global production networks (*foreign*). The *overall CO_2 intensity* is thus given by summing the *domestic* and *foreign CO_2 intensity*. The foregoing indices are so computed:

$$Direct\ CO_2\ intensity\ (j,k) = M_{(k-1)\times n+j,(k-1)\times n+j} \quad (7)$$

$$Domestic\ CO_2\ intensity\ (j,k) = \sum_{i=1}^{n} M_{(k-1)\times n+i,(k-1)\times n+j} \quad (8)$$

$$Foreign\ CO_2\ intensity\ (j,k) = \sum_{i=1}^{n} \sum_{\substack{m=1 \\ m\neq k}}^{c} M_{(m-1)\times n+i,(k-1)\times n+j} \quad (9)$$

$$Overall\ CO_2\ intensity\ (j,k) = Domestic\ CO_2\ intensity\ (j,k) + Foreign\ CO_2\ intensity\ (j,k) = \sum_{i=1}^{n} \sum_{m=1}^{c} M_{(m-1)\times n+i,(k-1)\times n+j} \quad (10)$$

A measure of the degree of internationalization of the GEC of the *j*-th industry of the *k-th* country can be also computed using the indices above. In particular, the degree of internationalization of the *j*-th industry of the *k-th* country is defined as the ratio between the *foreign CO_2 intensity* and the *overall CO_2 intensity*, i.e.:

$$Degree\ of\ \ internationalization\ (j,k) = \frac{Foreign\ CO_2\ intensity\ (j,k)}{Overall\ CO_2\ intensity\ (j,k)} = \frac{\sum_{i=1}^{n} \sum_{\substack{m=1 \\ m\neq k}}^{c} M_{(m-1)\times n+i,(k-1)\times n+j}}{\sum_{i=1}^{n} \sum_{m=1}^{c} M_{(m-1)\times n+i,(k-1)\times n+j}} \quad (11)$$

This index ranges between zero and one: it is equal to zero when all the CO_2 emissions driven by the final demand of industry *j* of country *k* are generated by domestic industries, i.e., within the country, whereas it is equal to one when all the CO_2 emissions are generated by foreign industries, i.e., outside the country. To know in

Table 2
Part of the M matrix (data in Kg of CO_2 per \$).

			Agriculture, Hunting, Forestry and Fishing	Mining and Quarrying	Food, Beverages and Tobacco	Textiles and Textile Products	Leather, Leather and Footwear	…	Wood and Products of Wood and Cork	Pulp, Paper, Paper , Printing and Publishing	Coke, Refined Petroleum and Nuclear Fuel	Chemicals and Chemical Products	Rubber and Plastics
			AUS	AUS	AUS	AUS	AUS	…	FRA	FRA	FRA	FRA	FRA
			s1	s2	s3	s4	s5	…	s6	s7	s8	s9	s10
Agriculture, Hunting, Forestry and Fishing	AUS	s1	0.1659	0.0003	0.0406	0.0164	0.0183	…	1.27E-05	3.4E-06	5.84E-06	7.29E-06	7.82E-06
Mining and Quarrying	AUS	s2	0.0038	0.1775	0.0060	0.0047	0.0052	…	7.45E-05	5.95E-05	0.000647	0.000125	0.000103
Food, Beverages and Tobacco	AUS	s3	0.0015	1.36E-04	0.0562	0.0011	0.0012	…	1.5E-06	9.77E-07	2.43E-06	2.69E-06	2.56E-06
Textiles and Textile Products	AUS	s4	9.12E-05	4.15E-05	1.73E-04	0.0677	0.0044	…	1.71E-07	1.83E-07	4.18E-07	2.85E-07	3.13E-07
Leather, Leather and Footwear	AUS	s5	2.12E-05	9.65E-06	4.03E-05	9.07E-04	0.0585	…	3.97E-08	4.32E-08	9.34E-08	6.61E-08	7.4E-08
…	…	…	…	…	…	…	…	…	…	…	…	…	…
Wood and Products of Wood and Cork	FRA	s6	1.15E-06	9.85E-07	1.26E-06	1.49E-06	1.66E-06	…	0.0390	0.0003	3.18E-05	8.42E-05	.1.24E-04
Pulp, Paper, Paper , Printing and Publishing	FRA	s7	6.16E-06	3.16E-06	1.51E-05	8.84E-06	9.85E-06	…	.8.12E-04	0.0635	.3.87E-04	0.0012	0.0011
Coke, Refined Petroleum and Nuclear Fuel	FRA	s8	4.21E-05	2.01E-05	3.34E-05	3.84E-05	4.29E-05	…	0.0045	0.0029	0.2390	0.0110	0.0035
Chemicals and Chemical Products	FRA	s9	.1.85 E-04	3.66E-05	9.19E-05	.1.11E-04	.1.24E-04	…	0.0013	0.0015	0.0012	0.1064	0.0081
Rubber and Plastics	FRA	s10	3.02E-06	2.07E-06	7.4E-06	5.41E-06	6.03E-06	…	1.52E-04	2.58E-04	0.0003	0.0004	0.0221

which countries the foreign emissions are generated, the elements of the column *(k-1)* × *n* + *j* of the *M* matrix, corresponding to emissions of industries in the same country, should be summed. For instance, the CO_2 emissions generated by all industries of the country *v* per each dollar of final demand of industry *j* of country *k* can be computed as follows:

$$\textit{Indirect } CO_2 \textit{ emissions } (v \leftarrow j,k) = \sum_{i=1}^{n} M_{(v-1)\times n+i,(k-1)\times n+j} \tag{12}$$

All these indices are useful to conduct the following analyses: (1) characterizing the GEC of an industry of a country; (2) comparing the same industry in different countries to identify similarities, differences, and benchmark; and (3) studying the evolution of the GEC of an industry of a country over time.

The *overall CO_2 intensity* index is particularly useful to support the analysis of decarbonization patterns of a given GEC over time. In particular, by computing this index for different years, it can be assessed whether and the extent to which the GEC has become less pollutant over time in terms of CO_2 emissions intensity. Changes in the *overall CO_2 intensity* are driven by two factors: (1) changes in the emission intensity of industries involved in the global supply chain; and (2) changes in the structure of the global supply chain. The effects of both these drivers can be computed by adopting a structural decomposition analysis (e.g., de Vries and Ferrarini, 2017; Nguyen et al., 2018; Wang et al., 2017). In fact, according to Equations (6) and (10), it follows that:

$$\begin{aligned} \textit{Overall } CO_2 \textit{ intensity}(j,k) &= \sum_{i=1}^{n}\sum_{m=1}^{c} M_{(m-1)\times n+i,(k-1)\times n+j} \\ &= \sum_{i=1}^{n}\sum_{m=1}^{c} e_i^m \cdot L_{(m-1)\times n+i,(k-1)\times n+j} \end{aligned} \tag{13}$$

The change in the *overall CO_2 intensity* of industry *j* of country *k* between two generic years *t* and *t*+Δ*t* (i.e., ΔOverall CO_2 intensity(j, k)) is so defined:

$$\Delta \textit{Overall } CO_2 \textit{ intensity}(j,k) = E_e(j,k) + E_L(j,k) \tag{14}$$

where $E_e(j,k)$ denotes the effect of changes in emission intensity of industries involved in the global supply chains, *ceteris paribus*, and $E_L(j,k)$ denotes the effect of changes in the structure of the global supply chains, *ceteris paribus*. For example, $E_e(j,k) = -a$ means that, *ceteris paribus*, the decarbonization of industries at the world level resulted in reducing the *overall CO_2 intensity* of industry *j* of country *k* by *a* Kg/\$ between years *t* and *t*+Δ*t*. Similarly, $E_L(j,k) = -b$ means that *ceteris paribus* the changes in the structure of global supply chain of industry *j* of country *k* resulted in reducing the *overall CO_2 intensity* of industry *j* of country *k* by *b* Kg/\$ between years *t* and *t*+Δ*t*. These two elements are computed as follows:

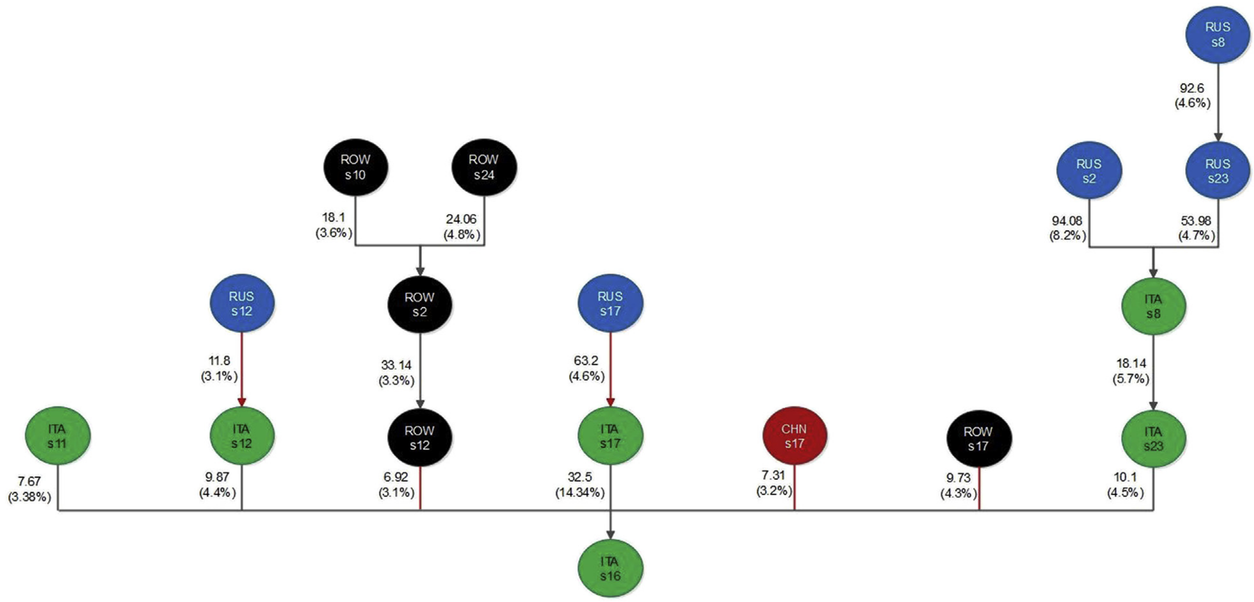

Fig. 1. GET of industry ITA_s16 computed for 2009. Red lines denote the flows from foreign sectors. Legend: s2 – "Mining and Quarrying"; s8 – "Coke, Refined Petroleum and Nuclear Fuel"; s10 – "Rubber and Plastics"; s12 – "Basic Metals and Fabricated Metal"; s17 – "Electricity, Gas and Water Supply"; s23 – "Inland Transport"; s24 – "Water Transport". (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Number of nodes and average number of nodes for each GET as a function of the selected value of threshold.

Threshold value (α)	Number of nodes	Average number of nodes for each GET
0	2059225	1435
0.005	645971	450.15
0.01	91742	63.93
0.015	31746	22.12
0.02	20536	14.31
0.025	13517	9.42
0.03	10275	7.16
0.035	7750	5.40
0.04	4803	3.35

$$E_e(j,k) = \sum_{i=1}^{n}\sum_{m=1}^{c} E_e(i,m\rightarrow j,k) = \sum_{i=1}^{n}\sum_{m=1}^{c}\frac{1}{2}\left[e_i^m(t+\Delta t) - e_i^m(t)\right]\left[L_{(m-1)\times n+i,(k-1)\times n+j}(t) + L_{(m-1)\times n+i,(k-1)\times n+j}(t+\Delta t)\right] \tag{15}$$

$$E_L(j,k) = \sum_{i=1}^{n}\sum_{m=1}^{c} E_L(i,m\rightarrow j,k) = \sum_{i=1}^{n}\sum_{m=1}^{c}\frac{1}{2}\left[e_i^m(t) + e_i^m(t+\Delta t)\right]\left[L_{(m-1)\times n+i,(k-1)\times n+j}(t+\Delta t) - L_{(m-1)\times n+i,(k-1)\times n+j}(t)\right] \tag{16}$$

The term $E_e(i,m\rightarrow j,k)$ in Eq. (15) denotes the impact on the *overall CO_2 intensity* of industry *j* of country *k* due to changes in the CO_2 intensity of industry *i* of country *m*, *ceteris paribus*.

In particular, $E_e(i,m\rightarrow j,k) < 0$ if industry *i* of country *m* reduced its CO_2 intensity between years *t* and $t+\Delta t$, otherwise $E_e(i,m\rightarrow j,k) \geq 0$. The term $E_L(i,m\rightarrow j,k)$ in Eq. (16) denotes the impact of changes in the involvement of industry *i* of country *m* in the global supply chain of industry *j* of country *k*, *ceteris paribus*. In particular, $E_L(i,m\rightarrow j,k) > 0$ if industry *j* of country *k* increased its demand for products of industry *i* of country *m* per dollar of final demand between years *t* and $t+\Delta t$, otherwise $E_L(i,m\rightarrow j,k) \leq 0$.

It is possible to compute both the effects at the country level. The effect of changes in CO_2 emission intensity of all industries of the *m*-th country can be assessed by simply summing $E_e(i,m\rightarrow j,k)$ corresponding to country *m*. Similarly, the effect of changes in the involvement in global supply chains of all industries of the *m*-th country can be assessed by simply summing $E_L(i,m\rightarrow j,k)$ corresponding to country *m*.

3.3. The Global Emission Trees

GETs are a condensed version of GECs. They can be obtained from GECs by adapting the methodology proposed by Zhu et al.

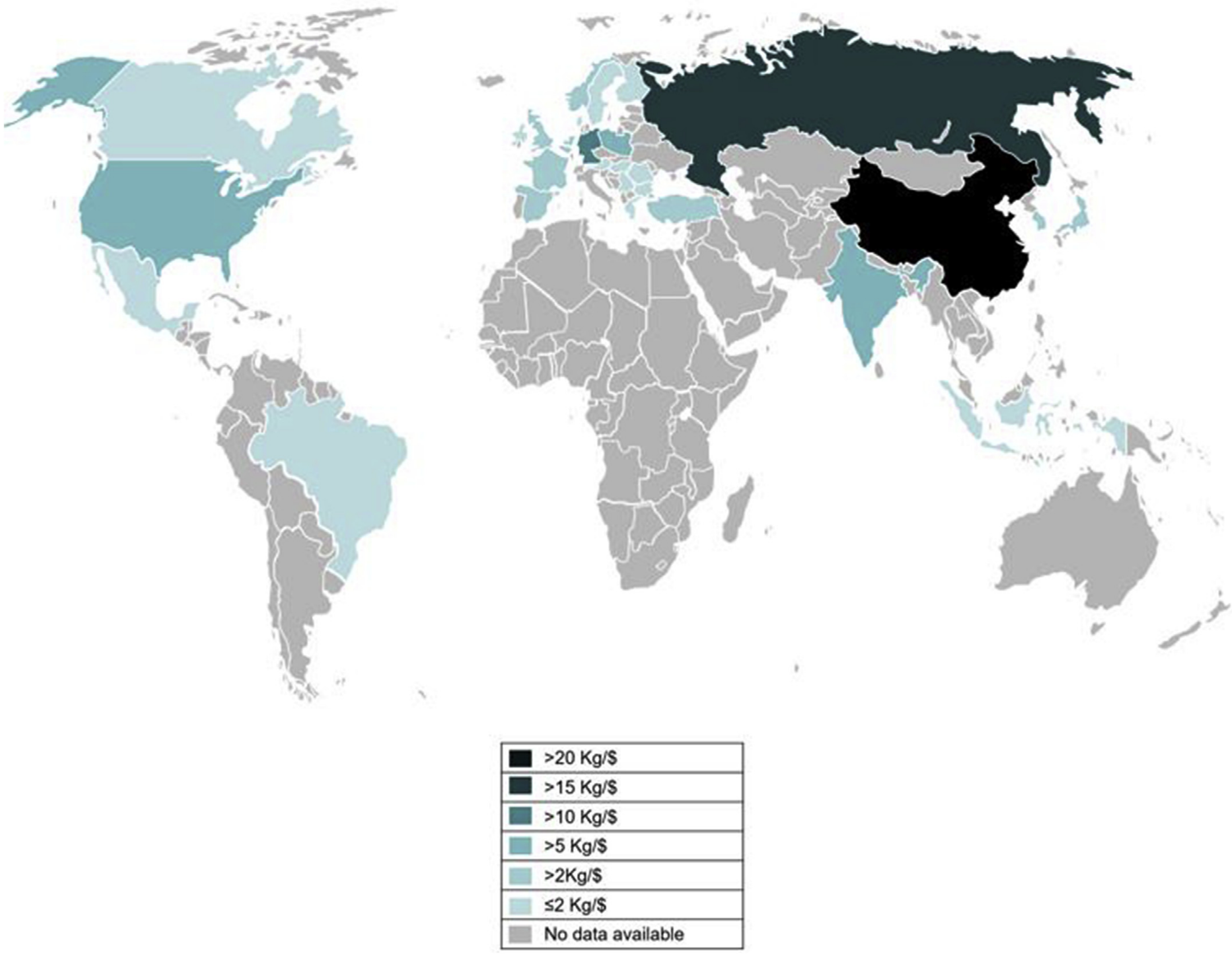

Fig. 2. Foreign CO_2 intensity of Italian "Transport Equipment" industry per country.

(2015) to compute the Global Value Trees from the Global Value Chains. For each industry available in the WIOD, first the industry as the root of the GET is chosen and a Bread First Search (BFS) algorithm is applied, starting from that node. At each step, the new nodes are added based on their emission contributions to the existing nodes. As a result, each GET captures the CO_2 emission flows from the leaf industries to the root industry. GETs easily produce a detailed topological view of the GECs, highlighting industries mainly responsible for indirect CO_2 emissions of the root node as well as the interdependencies among industries. In particular, this information is not immediately shown by the GEC but requires further analysis.

Since the GECs are almost completely connected, the GETs are built based on a threshold of the edge weight, which is denoted by α, in order to keep only the most essential emission contribution relationships for the root industry. In particular, only nodes contributing for at least the α percent of the total emissions due to the root node are considered (for instance, considering the *j*-th root node, the *i*-th node is added to the GET if and only if $\frac{M_{ij}}{\sum_{i=1}^{n \times c} M_{ij}} \geq \alpha$). As an example, Fig. 1 shows the GET rooted at Italy's "Manufacturing" industry (ITA_s16) in 2009 with $\alpha = 0.03$.

This means that the nodes at the first level of the tree (i.e., nodes from ITA_s11 – Other Non-Metallic Mineral to ITA_s23 – Inland Transport) are related to industries that contribute for at least the 3% of the global emissions driven by the final demand of the industry ITA_s16. For example, for each dollar of final demand of industry ITA_s16, 32.5 Kg of CO_2 are produced by industry ITA_s17 – Electricity, Gas and Water Supply, accounting for 14.34% of the *overall CO_2 intensity* of the industry ITA_s16. The nodes at the second level of the tree are related to industries that contribute for at least the 3% of the total emissions due to the correspondent first-level root node. For example, 63.2 Kg of CO_2, accounting for 4.6% of the overall CO_2 emissions due to industry ITA_s17, are generated per dollar of final demand of industry ITA_s17.

Changing the value of α would result in a different GET. In particular, the lower the value of α, the higher the number of nodes for each level of the GET will be. If $\alpha = 0$, the first level of the GET would be composed by $n \times c$ nodes. However, too many nodes reduce the usefulness of GET to easily highlight the main industries responsible for indirect emissions, since most of nodes are included. Alternatively, too high value of α risks to not take into account important nodes. In this regard, Table 3 shows the total number of nodes and the average number of nodes for each GET as a

Table 4
Direct CO_2 intensity, domestic CO_2 intensity, foreign CO_2 intensity, overall CO_2 intensity, and degree of internationalization computed for the "Transport Equipment" industry of all countries for 2009.

	direct CO_2 intensity [Kg/$]	domestic CO_2 intensity [Kg/$]	foreign CO_2 intensity [Kg/$]	overall CO_2 intensity [Kg/$]	Degree of Internationalization
AUS	8.76	244.47	169.13	413.60	40.89%
AUT	6.92	43.08	192.24	235.31	81.70%
BEL	8.19	44.37	240.78	285.14	84.44%
BGR	662.44	1171.87	316.24	1488.11	21.25%
BRA	14.76	146.53	102.07	248.60	41.06%
CAN	28.87	141.42	189.57	330.99	57.27%
CHN	64.40	1062.61	108.69	1171.29	9.28%
CYP	1840.20	1975.61	172.14	2147.76	8.01%
CZE	12.37	124.59	244.62	369.21	66.25%
DEU	13.06	108.92	178.24	287.16	62.07%
DNK	26.88	57.80	165.71	223.51	74.14%
ESP	25.49	126.15	143.89	270.04	53.28%
EST	302.59	528.50	211.21	739.72	28.55%
FIN	8.53	114.33	190.23	304.56	62.46%
FRA	16.27	63.76	157.38	221.14	71.17%
GBR	28.00	125.22	176.08	301.30	58.44%
GRC	91.83	252.69	199.09	451.78	44.07%
HUN	8.68	77.06	233.86	310.92	75.22%
IDN	117.81	327.33	120.79	448.12	26.95%
IND	171.94	1370.36	171.74	1542.11	11.14%
IRL	88.75	142.98	206.87	349.85	59.13%
ITA	**35.25**	**140.81**	**142.24**	**283.05**	**50.25%**
JPN	24.63	204.28	111.02	315.30	35.21%
KOR	31.60	394.56	240.30	634.86	37.85%
LTU	29.20	138.91	203.44	342.34	59.43%
LUX	0.00	18.85	220.01	238.86	92.11%
LVA	64.26	176.93	247.64	424.57	58.33%
MEX	29.99	175.23	194.76	370.00	52.64%
MLT	8.84	343.72	166.48	510.21	32.63%
NLD	13.20	61.23	210.51	271.74	77.47%
POL	23.88	272.26	199.92	472.18	42.34%
PRT	2.77	70.51	158.49	229.01	69.21%
ROU	45.20	303.01	174.24	477.25	36.51%
RUS	70.44	1097.85	107.71	1205.56	8.93%
SVK	23.04	71.09	253.38	324.46	78.09%
SVN	11.76	93.18	267.15	360.33	74.14%
SWE	8.26	52.45	190.11	242.56	78.38%
TUR	31.12	240.22	185.72	425.94	43.60%
TWN	35.79	351.39	242.16	593.54	40.80%
USA	41.88	249.92	134.05	383.97	34.91%

function of the selected value of the threshold. Therefore, α should be set to obtain the right trade-off between completeness and complication.

Based on GETs, the following indices at the industry level can be computed:

- the *contribution coefficient* of industry *j* of country *k* – C (j,k), defined as the number of GETs where the industry *j* of country *k* is depicted;
- the *first-level contribution coefficient* of industry *j* of country *k* – F (j,k), defined as the number of GETs where the industry *j* of country *k* is depicted at the first level;
- the *national contribution coefficient* of industry *j* of country *k* – NC(j,k), defined as the number of GETs of the *k*-th country where the industry *j* is depicted;
- the *national first-level contribution coefficient* of industry *j* of country *k* – NF(j,k), defined as the number of GETs of *k*-th country where the industry *j* is depicted at the first level.

These indices provide information on the relevance of the industry *j* of country *k* in the production of CO_2 emissions at global and national level and thus can be used to design more effective decarbonization strategies. For example, industries with high (national) contribution coefficient are those where a reduction of CO_2 intensity can be more effective at a global (national) level. This is truer when the first-level contribution coefficient is high, since this means that the industry provides a great amount of emissions.

The indices above are computed as follows:

$$C(j,k) = \sum_{k=1}^{n} \sum_{m=1}^{c} A_{jkim} \quad (17)$$

$$F(j,k) = \sum_{k=1}^{n} \sum_{m=1}^{c} B_{jkim} \quad (18)$$

$$NC(j,k) = \sum_{m=1}^{c} A_{jkim} \quad (19)$$

$$NF(j,k) = \sum_{m=1}^{c} B_{jkim} \quad (20)$$

In particular, $A_{jkim} = 1$ if the node of *j*-th industry of the *k*-th country belongs to the GET of the *i*-th industry of the *m*-th country, otherwise $A_{jkim} = 0$. Similarly, $B_{jkim} = 1$ if the node of *j*-th industry of the *k*-th country belongs to the first level of the GET of the *i*-th industry of the *m*-th country, otherwise $B_{jkim} = 0$. Of course, it results that $F(j,k) \le C(j,k)$ and $NF(j,k) \le NC(j,k)$ $\forall$ *j*, *k*. In particular, the higher *C(j,k)* and *F(j,k)* (*NC(j,k)* and *NF(j,k)*), the higher the

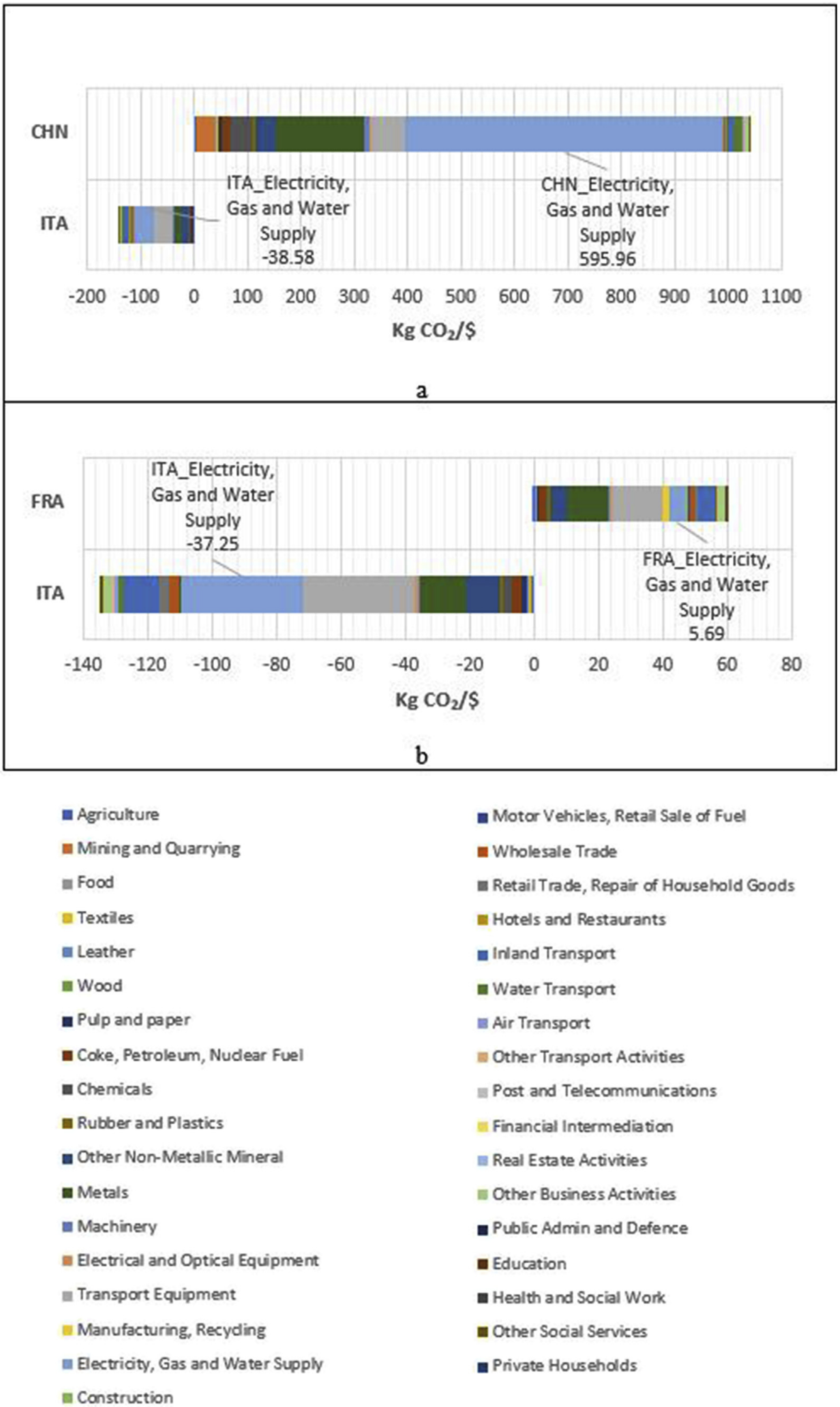

Fig. 3. Impact on local CO_2 emissions resulting from shifting one dollar of final demand of Italian "Transport Equipment" industry in China (a) and France (b).

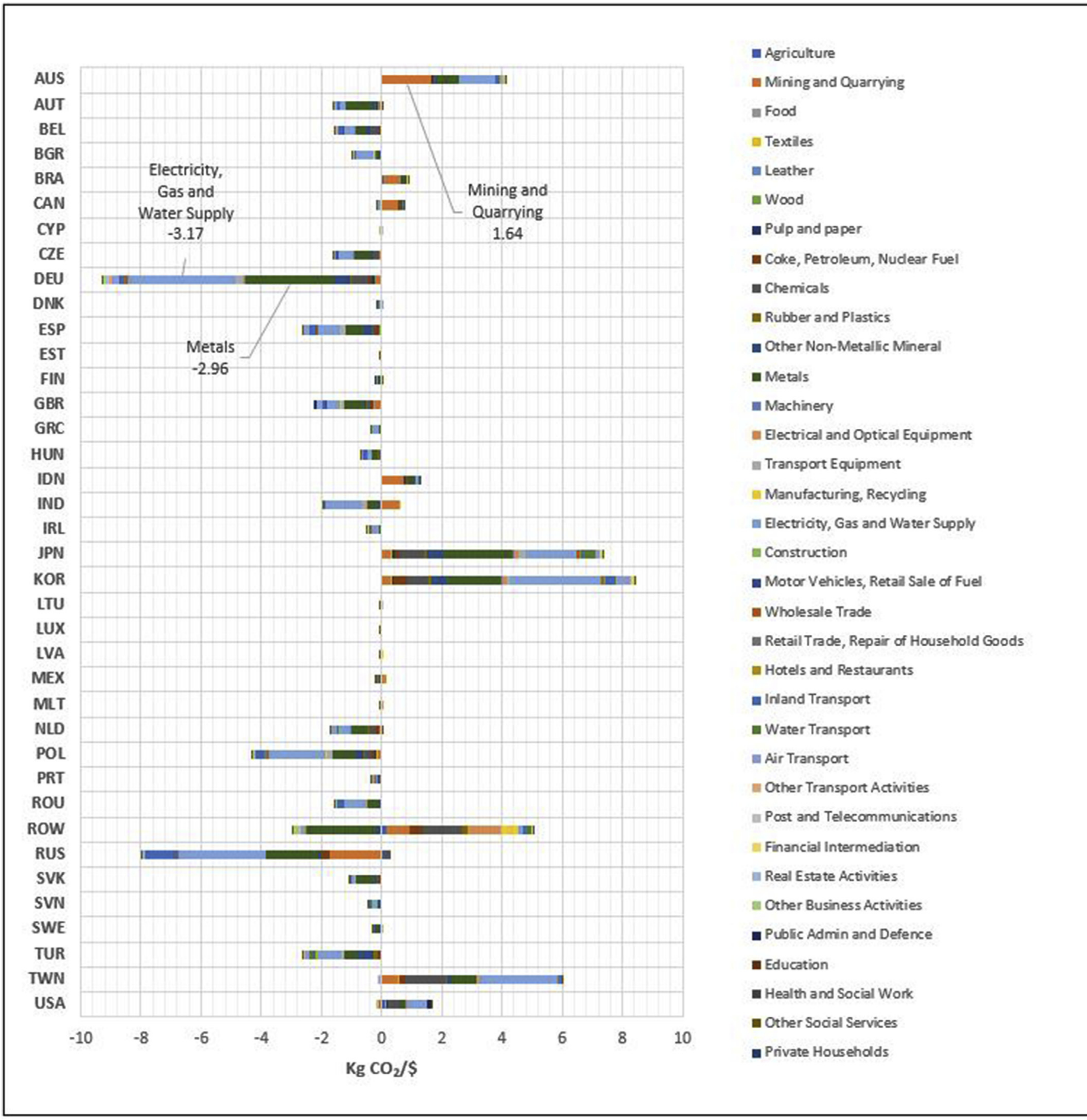

Fig. 4. Impact on domestic CO_2 emissions at country level resulting from shifting one dollar of final demand of Italian "Transport Equipment" industry in China.

importance of that node for the CO_2 emissions at the global (national) level, i.e., that node significantly contributes to emissions indirectly generated by many other industries.

4. Numerical analyses

This Section shows how to use the GECs and the GETs for conducting alternatives analyses. In particular, Section 4.1 addresses applications of GECs aimed at analyzing a selected industry. Section 4.2 presents how to compute the GETs of Italian "Transport Equipment" industry in three years and how to investigate single GETs.

4.1. Global Emission Chains

This Section is divided into three subsections. Section 4.1.1 describes how to analyze the GEC of the Italian "Transport Equipment" industry. Section 4.1.2 addresses the comparison among the GECs of this industry in different countries. Finally, Section 4.1.3 provides a global analysis of decarbonization patterns of the sector over time by using data of the GECs.

4.1.1. Analysis of GEC of a specific industry

The GEC of the Italian "Transport Equipment" industry in 2009 is

Fig. 5. Impact on domestic CO_2 emissions at country level resulting from shifting one dollar of final demand of Italian “Transport Equipment” industry in France.

considered for the analysis. This year was chosen because it is the last available year for data concerning the CO_2 emission intensity of industries, information required to compute Eq. (5). The “Transport Equipment” industry was chosen because it highly contributes to Italian GDP but it is also responsible for high amount of CO_2 emissions. It has also undergone a structural change in global supply chains that our tool permits to analyze in terms of CO_2 emissions.

This GEC is computed by using the procedure described in Section 3.2 (the matrix M is given in Supplementary materials). Then, this GEC is analyzed using the indices proposed in Equations (7)-(11). Results show that the Italian “Transport Equipment” industry is directly responsible for producing 35.25 Kg of CO_2 per each dollar of final demand (*direct CO_2 intensity*). However, these direct emissions account only for 12.45% of the *overall CO_2 intensity*. In fact, 283.05 Kg of CO_2 are globally produced per each dollar of final demand: in particular, 140.81 Kg are produced within the Italian boundaries (*domestic CO_2 intensity*) due to the existence of domestic production networks (upstream sectors involved) and 142.24 Kg are produced in foreign countries (*foreign CO_2 intensity*)

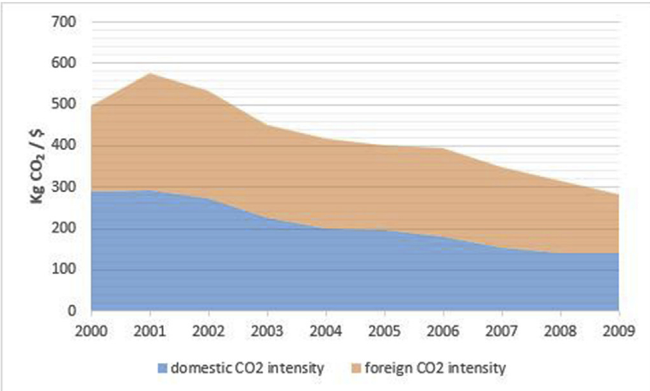

Fig. 6. Overall CO_2 intensity for the Italian "Transport Equipment" industry from 2000 to 2009. For each year, the contribution of domestic CO_2 intensity and the foreign CO_2 intensity if highlighted.

due to the involvement of Italian "Transport Equipment" industry in global production networks (upstream sectors involved abroad). Hence, the *degree of internationalization* of this GEC is 50.25%. This is not surprising, given the increasing complexity of the products developed by the sector that require increasing specialization. It is also explained by the growing adoption of global sourcing policy and off-shoring practice by Italian firms.

Countries, where the indirect emissions of the Italian "Transport Equipment" industry are generated, are depicted in Fig. 2 (data are computed by using Eq. (12)). The three countries where the highest amount of CO_2 is produced are China (2.07 kg/$), Russia (18.61 kg/$), and Germany (12.75 kg/$).

Hence, this tool can be easily used to forecast the environmental impacts (in terms of CO_2 emissions) due to changes in the final demand of a given industry of a given country. For example, one dollar increase in final demand of the Italian "Transport Equipment" industry would result in increasing CO_2 emissions produced in the USA by 5.79 Kg and in India by 5.58 Kg. More detailed information about which single industries in the foreign countries generate CO_2 emissions triggered by the Italian "Transport Equipment" industry can be given by analyzing the GET of this industry, as described next in Section 4.2. In fact, this is properly designed to accomplish this issue in an easy manner.

4.1.2. Comparison among the GECs of the same industry in different countries

The values of *direct CO_2 intensity*, the *domestic CO_2 intensity*, the *foreign CO_2 intensity*, the *overall CO_2 intensity*, and the degree of internationalization for the GECs of "Transport Equipment" industries of diverse countries computed for 2009 are depicted in Table 4. These data significantly diverge among countries. Consider the *overall CO_2 intensity*: values of this index range between 221.14 kg/$ (France) and 2147.76 kg/$ (Cyprus). Hence, producing "Transport Equipment" products in Cyprus is ten times more pollutant (in terms of CO_2 emissions) at the global level than producing the same output in France. French "Transport Equipment Industry" can be then considered as the benchmark for producing transport equipment with the lowest level of CO_2 emissions. In fact, this GEC would represent the cleaner global production network in the world, concerning the production of transportation equipment.

As to the degree of internationalization, the values range from 8.02% (Cyprus) to 92.11% (Luxembourg). It can be noted that countries with the highest *overall CO_2 intensity* (i.e., Cyprus, Bulgaria, China, India, and Russia) have the lowest degree of internationalization. This means that, for the above-mentioned countries, the "Transport Equipment" industry is high-pollutant in terms of domestic CO_2 emissions generated.

By comparing GECs of the same industry of different countries, the environmental impact of final demand shift can be assessed at both global and local level in a detailed manner.

Assuming that one dollar of final demand for the sector "Transport Equipment" shifts from Italy to China/France (i.e., that final demand of Italian "Transport Equipment" industry is reduced by one dollar while the final demand of Chinese/French "Transport Equipment" industry is increased by one dollar simultaneously), this implies that the change in the amount of CO_2 produced at the global level will be the difference between the *overall CO_2 intensity* of the Italian "Transport Equipment" and the *overall CO_2 intensity* of the Chinese/French "Transport Equipment". Notice that this change is positive in the case of demand-shift towards China (+888.24 Kg) and negative in the case of France (−61.91 Kg). This is due to the fact that the *overall CO_2 intensity* of Italian "Transport Equipment" industry is lower than the *overall CO_2 intensity* of Chinese "Transport Equipment" industry but higher than the *overall CO_2 intensity* of French "Transport Equipment" industry. The impact on the amount of CO_2 produced within these countries can be easily assessed. If one dollar of final demand for the "Transport Equipment" industry (s15) shifts from Italy to China, the amount of CO_2 emissions produced in Italy decreases by 140.1 Kg, while the amount of CO_2 emissions produced in China increases by 1041.9 Kg (Fig. 3a). Alternatively, if one dollar of final demand for the "Transport Equipment" industry (s15) shifts from Italy to France, the amount of CO_2 emissions produced in Italy decreases by 134.8 Kg, while the amount of CO_2 emissions produced in France increases by 60.51 Kg (Fig. 3b). Fig. 3 also displays which specific industries are responsible for these changes in CO_2 emissions. For example, if one dollar of final demand for the "Transport Equipment" industry (s15) shifts from Italy to China, CO_2 emissions produced by Italian "Electricity, Gas and Water Supply" industry (ITA_s17) decrease by 38.58 Kg but CO_2 emissions produced by Chinese "Electricity, Gas and Water Supply" industry (CHN_s17) increase by 595.96 Kg (Fig. 3a). Similarly, if one dollar of final demand for the "Transport Equipment" industry (s15) shifts from Italy to France, CO_2 emissions produced by Italian "Electricity, Gas and Water Supply" industry (ITA_s17) decrease by 37.25 Kg but CO_2 emissions produced by French "Electricity, Gas and Water Supply" industry (FRA_s17) increase by 5.69 Kg (Fig. 3b).

Furthermore, shifting one dollar of final demand for the "Transport Equipment" industry from Italy to China/France impacts on domestic CO_2 emissions of other countries. In this regard, the impacts on domestic CO_2 emissions at each country, resulting from shifting one dollar of final demand of Italian "Transport Equipment" industry to China and France, are depicted in Fig. 4 and Fig. 5, respectively.

It can be noted that shifting one dollar of final demand for the "Transport Equipment" industry from Italy to China would contribute to reduce the domestic CO_2 emissions of almost all the European countries, while it would be responsible for increasing the domestic CO_2 emissions of the main Asian countries (Fig. 4). Alternatively, shifting one dollar of final demand for the "Transport Equipment" industry from Italy to France would contribute to increase domestic CO_2 emissions of European countries while decreasing CO_2 emissions produced by countries belonging to the Rest-of-the-World (Fig. 5). Furthermore, it can be noted that the industries mainly responsible for these changes are "Mining and Quarrying" (s2), "Basic Metals and Fabricated Metal" (s12), and "Electricity, Gas and Water Supply" (s17). For example, let us consider the case of Germany. Shifting one dollar of final demand of Italian "Transport Equipment" industry in China would decrease

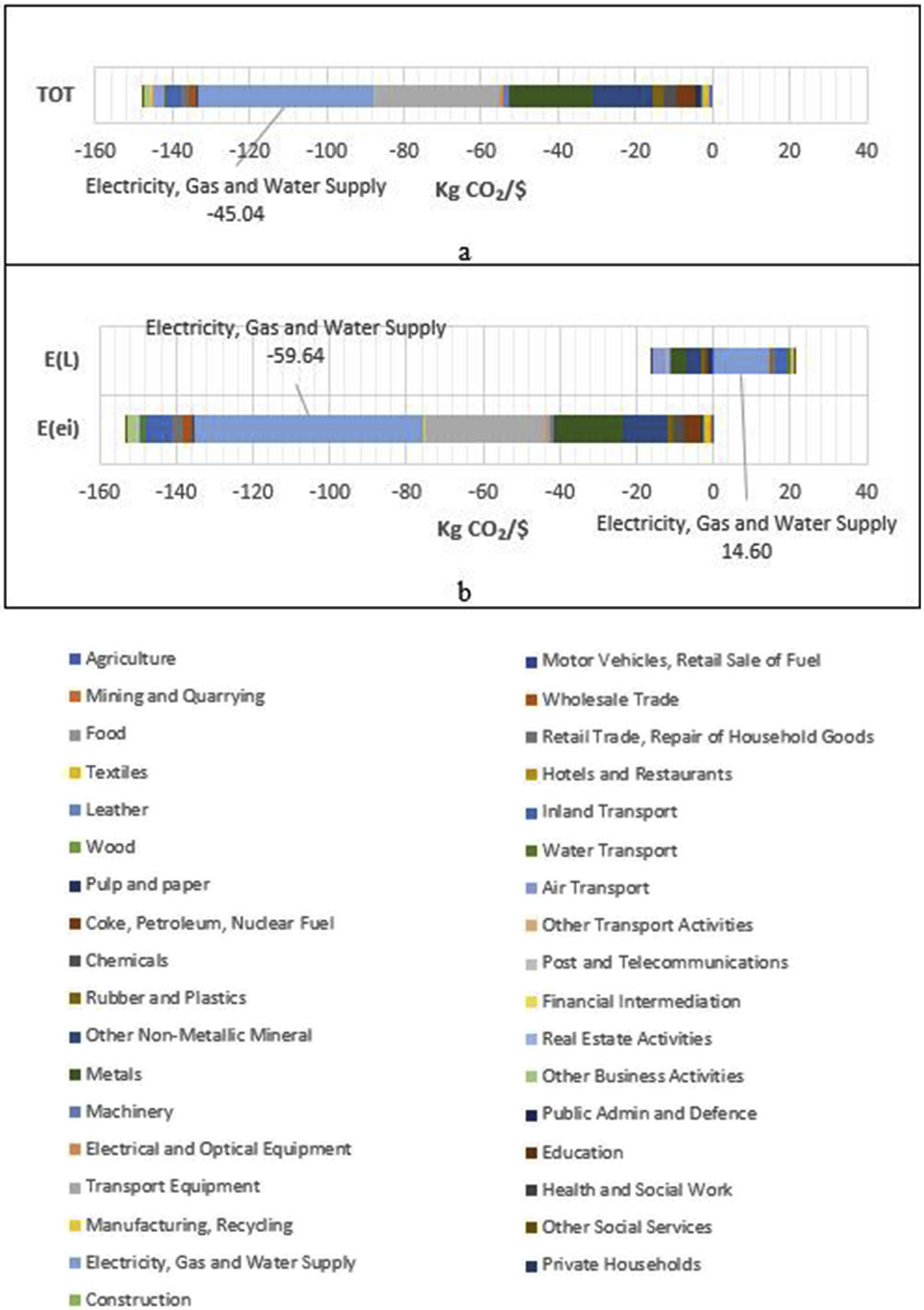

Fig. 7. (a) Contribution of each Italian industry to the reduction in the domestic CO_2 intensity of Italian "Transport Equipment" industry; (b) effects due to reductions in CO_2 intensity and changes in supply chain structure for each Italian industry.

CO_2 emissions at the national level by 9.27 Kg (Fig. 4), while shifting one dollar in France would increase CO_2 emissions by 5.20 Kg (Fig. 5). When analyzing the involved industries, it can be noted that shifting one dollar of final demand to China would reduce CO_2 emissions of German "Basic Metals and Fabricated Metal" and "Electricity, Gas and Water Supply" industry by 2.96 Kg and 3.57 Kg, respectively (Fig. 4). On the contrary, shifting one dollar of final demand to France would increase CO_2 emissions of German "Basic Metals and Fabricated Metal" and "Electricity, Gas and Water Supply" industry by 1.19 Kg and 1.87 Kg, respectively (Fig. 5). Interestingly, it can be noted that even the effects for Italy can be different. In fact, the domestic CO_2 emissions would be reduced by 140.11 Kg in the former case and by 134.83 Kg in the latter case (see Fig. 3). This is due to the different structures of global supply chains of Chinese and French "Transport Equipment" industry. In fact, the effects of these changes are highly country-specific, depending on

Table 5
Changes in foreign CO_2 intensity of Italian "Transport Equipment" industry between 2000 and 2009 per country. The first column highlights the effects of changes in the emission intensity. The second column highlights the effects of changes in the global supply chains.

	E_e [Kg/$]	E_L [Kg/$]	Tot [Kg/$]
AUS	−1.59	−0.58	**−2.17**
AUT	−2.32	0.84	**−1.48**
BEL	−3.50	−1.04	**−4.54**
BGR	−4.84	1.42	**−3.42**
BRA	−1.07	−0.22	**−1.29**
CAN	−1.55	−0.96	**−2.50**
CHN	−22.74	27.61	**4.87**
CYP	−0.09	0.04	**−0.05**
CZE	−2.84	1.79	**−1.05**
DEU	−16.94	4.42	**−12.53**
DNK	−0.25	−0.01	**−0.26**
ESP	−4.39	1.82	**−2.57**
EST	−0.15	0.10	**−0.04**
FIN	−0.78	−0.48	**−1.26**
FRA	−5.40	−1.91	**−7.31**
GBR	−2.20	−2.57	**−4.77**
GRC	−0.67	0.09	**−0.58**
HUN	−1.18	0.71	**−0.46**
IDN	−0.81	0.34	**−0.47**
IND	−2.16	1.51	**−0.65**
IRL	−0.86	0.89	**0.03**
ITA	−153.06	5.42	**−147.65**
JPN	−1.13	−1.17	**−2.29**
KOR	−2.13	1.54	**−0.59**
LTU	−0.12	0.09	**−0.03**
LUX	−0.04	0.00	**−0.04**
LVA	−0.05	0.03	**−0.02**
MEX	−0.30	−0.28	**−0.58**
MLT	−0.02	0.04	**0.03**
NLD	−2.52	0.16	**−2.35**
POL	−8.38	6.51	**−1.87**
PRT	−0.85	0.25	**−0.60**
ROU	−3.23	2.16	**−1.07**
RUS	−1.09	3.36	**2.28**
SVK	−1.04	0.87	**−0.17**
SVN	−0.39	0.15	**−0.24**
SWE	−0.17	−0.11	**−0.28**
TUR	−1.66	0.95	**−0.71**
TWN	0.84	−0.68	**0.16**
USA	−3.38	−4.75	**−8.13**

the involvement of domestic industries in the above-mentioned global supply chains.

4.1.3. Analysis of decarbonization patterns over time

Fig. 6 displays the values of the *overall CO_2 intensity* of the Italian "Transport Equipment" industry over time from 2000 to 2009, distinguishing the values of *domestic CO_2 intensity* and *foreign CO_2 intensity*.

The industry has followed a decarbonization pathway. The *overall CO_2 intensity* decreases from 497.17 kg/$ to 283.05 kg/$ from 2000 to 2009. The effect played by changes in CO_2 emissions intensity is $E_L = 49.6\ Kg/\$$, while the effect due to changes in the structure of global supply chains is $E_e = -263.72\ Kg/\$$, assessed by using Equations (15) and (16), respectively. This means that, without changes in global supply chains, CO_2 emissions would have decreased by 263.72 Kg per dollar of final demand of Italian "Transport Equipment" industry while, without changes in the CO_2 emission intensity of single industries, CO_2 emissions would have increased by 49.6 Kg per dollar of final demand of Italian "Transport Equipment" industry. These data highlight that the decarbonization of the GEC of Italian "Transport Equipment" industry has been driven by reductions in the emission intensity of industries at the global level, while changes in the global supply chains played a negative role on the environmental sustainability of this chain. Fig. 7a shows that the *domestic CO_2 intensity* of Italian "Transport Equipment" industry (s15) decreased by 147.65 kg/$, highlighting the contribution of each Italian industry to this reduction. For example, it can be noted that the "Electricity, Gas and Water Supply" industry (s17) contributed to reduce the *domestic CO_2 intensity* of the "Transport Equipment" industry by 45.04 kg/$. Fig. 7b shows how much changes in the CO_2 emission intensity (−59.64 kg/$) and changes in the domestic supply chains (+14.60 kg/$) contributed to this reduction.

As shown in Fig. 6, the *foreign CO_2 intensity* of the Italian "Transport Equipment" industry decreased by 31.85% (from 208.71 kg/$ to 142.24 kg/$) from 2000 to 2009. The contribution of each country involved in the emission chain can be easily assessed (Table 5). The indirect CO_2 emissions generated per dollar of final demand of Italian "Transport Equipment" industry decreased in all countries except for China, Ireland, Malta, Russia, and Taiwan (see the third column). In particular, China is the country mostly contributing to increasing the *overall CO_2 intensity* of Italian "Transport Equipment" industry (+4.87 kg/$). However, when decomposing this effect as driven by changes in CO_2 intensity of Chinese industries (first column of Table 5) and changes in the involvement of Chinese industries in the supply chain of Italian "Transport Equipment" industry (second column of Table 5), two different trends can be highlighted. First, the data show that China puts a lot of efforts in decarbonizing its industries: in fact, *ceteris paribus*, the CO_2 generated by Chinese industries per dollar of final demand of Italian "Transport Equipment" industry would have decreased by 22.74 Kg, mainly driven by the decarbonization of two industries: "Basic Metals and Fabricated Metal" (CHN_s12), which contributed with a reduction of 4.07 Kg of CO_2 produced per dollar of Italian "Transport Equipment" industry, and "Electricity, Gas and Water Supply" (CHN_s17), which contributed with a reduction of 12.95 Kg of CO_2 produced per dollar of Italian "Transport Equipment" industry (see Fig. 8). However, as indicated by data in Table 5, the higher involvement of Chinese industries in the supply chain of Italian "Transport Equipment" industry resulted in increasing CO_2 emissions produced: *ceteris paribus*, the CO_2 generated by Chinese industries per dollar of final demand of Italian "Transport Equipment" industry would have increased by 27.61 Kg, mainly driven by two industries: "Basic Metals and Fabricated Metal" (CHN_c12), which contributed with an increase of 4.48 Kg of CO_2 produced per dollar of Italian "Transport Equipment" industry, and "Electricity, Gas and Water Supply" (CHN_s17), which contributed with an increase of 16.75 Kg of CO_2 produced per dollar of Italian "Transport Equipment" industry (see Fig. 9).

4.2. Global Emission Trees

This Section is divided into two subsections. Section 4.2.1 describes how to analyze the GET of this industry and Section 4.2.2 the GETs of this industry in different countries are compared.

4.2.1. Analysis of single GETs

The GETs for the Italian "Transport Equipment" industry (ITA_s15) computed for 2000, 2005, and 2009 by adopting $\alpha = 0.03$ are displayed in Fig. 10. Consider the GET computed for 2009 (Fig. 10c): per each dollar of final demand of this industry, 11.65 Kg of CO_2 (4.12% of the *overall CO_2 intensity*) are produced by Italian "Other Non-Metallic Mineral" (ITA_s11), 14.93 Kg of CO_2 (5.2%) are produced by Italian "Basic Metals and Fabricated Metal" (ITA_s12), 38.76 Kg of CO_2 (13.69%) are produced by Italian "Electricity, Gas and Water Supply" (ITA_s17), 11.37 Kg of CO_2 (4.01%) are produced by Chinese "Electricity, Gas and Water Supply" (CHN_s17), 9.98 Kg of CO_2 (3.53%) are produced by rest-of-the-world "Electricity, Gas and Water Supply" (ROW_s17), and 11.4 Kg of CO_2 (4.02%) are

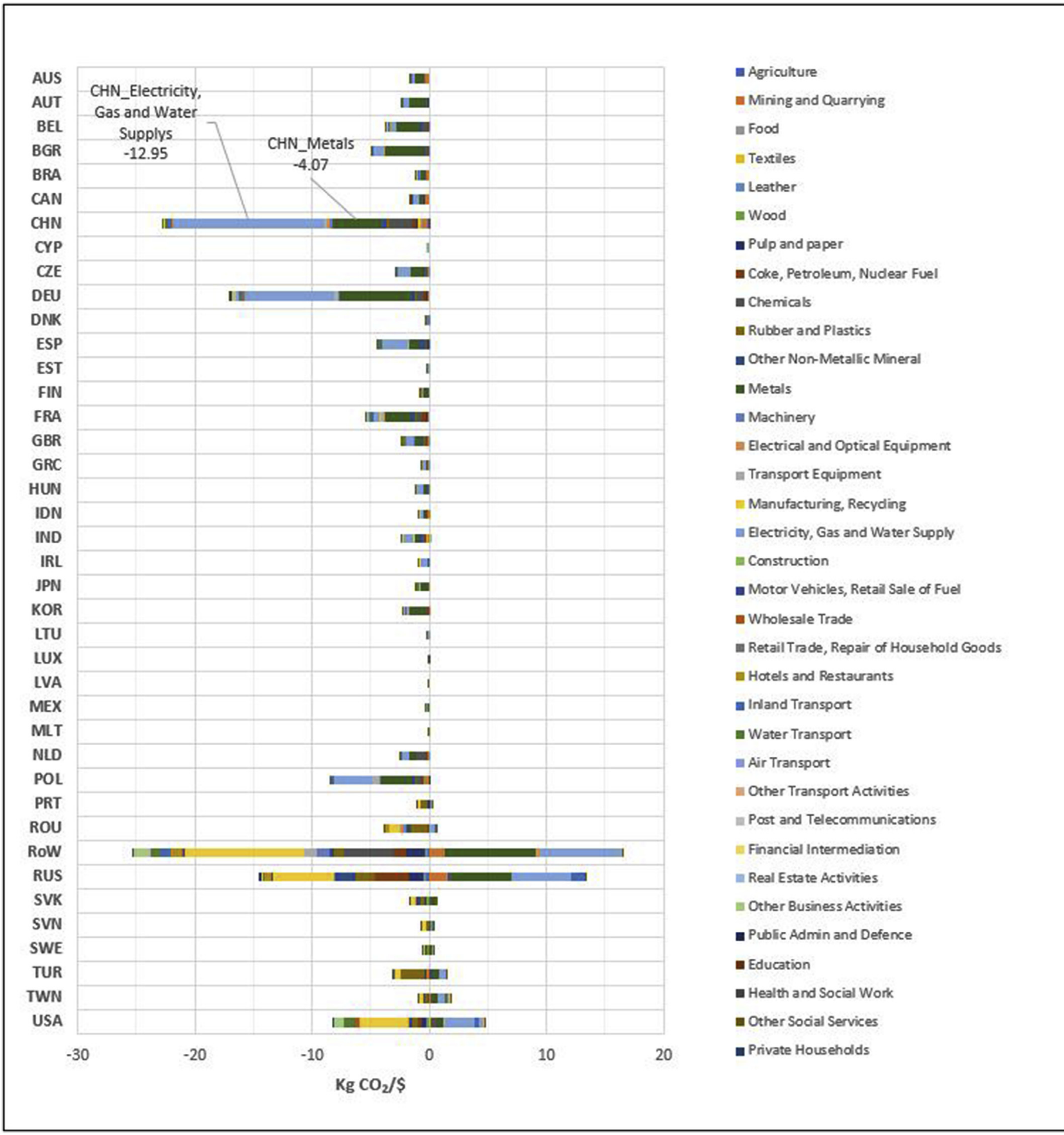

Fig. 8. Effects played by changes in CO_2 emissions intensity of single industries on the foreign CO_2 intensity of Italian "Transport Equipment" industry.

produced by Italian "Inland Transport" (ITA_s23). In turn, per each dollar of final demand of industry ITA_s12, 11.8 Kg of CO_2 (3.1% of the *overall CO_2 intensity*) are produced by Russian "Basic Metals and Fabricated Metal" (RUS_s12) and 15.47 Kg of CO_2 (4.21%) are produced by rest-of-the-world "Basic Metals and Fabricated Metal" (ROW_s12).

Fig. 10 highlights how the GET structures have become more complex over time, as a consequence of greater international trade. Furthermore, progressive globalization of the emission flows can be highlighted. In fact, in 2000 the GET was made by four nodes and no foreign industries significantly contributed to the overall CO_2 emission of industry ITA_s15; in 2009 the tree for the same industry is made by 17 nodes and the presence of Chinese and Russian industries, as well as industries belonging to the Rest of World (RoW), can be noted. This is consistent with data in Fig. 2, which highlights the role played by China and Russia on the *overall CO_2 intensity* of Italian "Transport Equipment" industry.

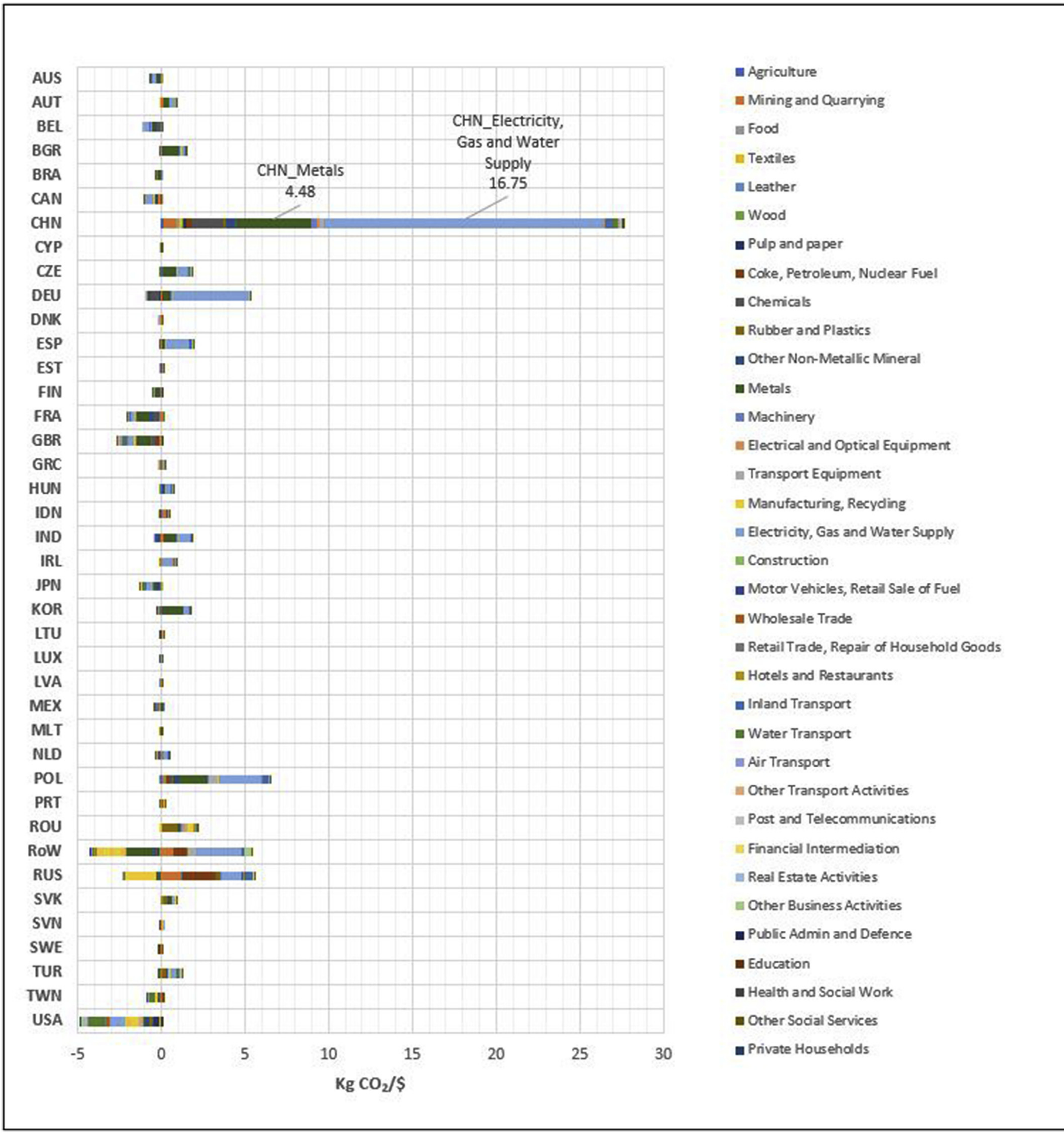

Fig. 9. Effects played by changes in global supply chains of single industries on the foreign CO_2 intensity of Italian "Transport Equipment" industry.

4.2.2. Comparison among different GETs of same industry in different countries

The GETs rooted at Rumanian "Transport Equipment" industry (ROU_s15) and at Austrian "Transport Equipment" industry (AUT_s15) in 2009 are displayed in Fig. 11a and Fig. 11b, respectively. The reader can easily appreciate how the above-mentioned GETs are different in terms of structure.

Comparing the GETs' structure, useful information can be easily captured. First, it can be noted that the Austrian GET has more nodes (12 vs. 5) and levels (3 vs. 1) than Rumanian GET. The number of nodes and levels is representative of the structural complexity of the GEC of the root node. Second, four industries are responsible for 51.28% of the *overall CO_2 intensity* of Rumanian "Transport Equipment" industry (Fig. 11a) whilst the six industries at the first level of the GET are responsible for 29.52% of the *overall CO_2 intensity* of Austrian "Transport Equipment" industry (Fig. 11b). Third, Austria has a more international GET than Romania. In fact, the Rumanian GET shows that only domestic industries significantly contribute to

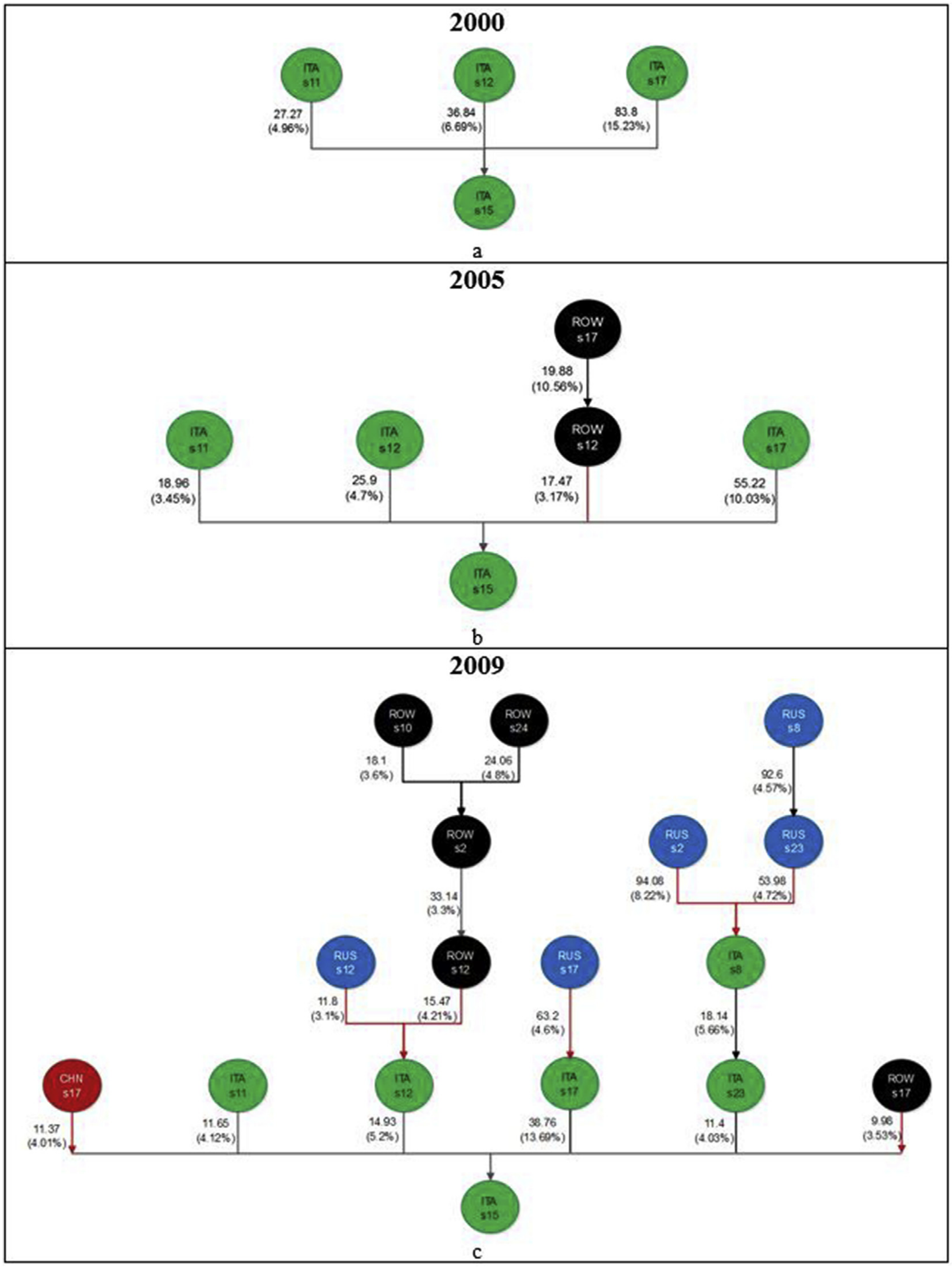

Fig. 10. GET for Italian "Transport Equipment" industry (ITA_s15) computed for 2000 (a), 2005 (b), and 2009 (c). Legend: s2 – "Mining and Quarrying"; s8 – "Coke, Refined Petroleum and Nuclear Fuel"; s10 – "Rubber and Plastics"; s11 – "Other Non-Metallic Mineral"; s12 – "Basic Metals and Fabricated Metal"; s17 – "Electricity, Gas and Water Supply"; s23 – "Inland Transport"; s24 – "Water Transport".

the indirect CO_2 emission of industry ROU_s15. Alternatively, the Austrian GET shows that only one domestic sector (AUT_s12 – Basic Metals and Fabricated Metal) contributes by more than 3% to the indirect CO_2 emissions of industry AUT_s15 but industries from Germany, China, and RoW have an important role into the GEC of industry AUT_s15. Finally, the different industries that significantly contribute to the overall CO_2 emissions of "Transport Equipment" industry in Romania and China can be easily highlighted. In this regard, whilst in the Rumanian "Other Non-Metallic Mineral" (s11) "Inland Transport" (s23) industries contribute by more than 3% to the overall CO_2 emissions of "Transport Equipment" industry, for Austria these industries do not provide any significant contribution. These differences suggest that different policy measures could be conducted in different countries to decarbonizing the same industry. In fact, whilst reducing the emission intensity of Rumanian "Electricity, Gas and Water Supply" industry (ROU_s17) by 1% would reduce the overall emission intensity of industry ROU_s15 by 0.366%, reducing the emission intensity of Austrian "Electricity, Gas

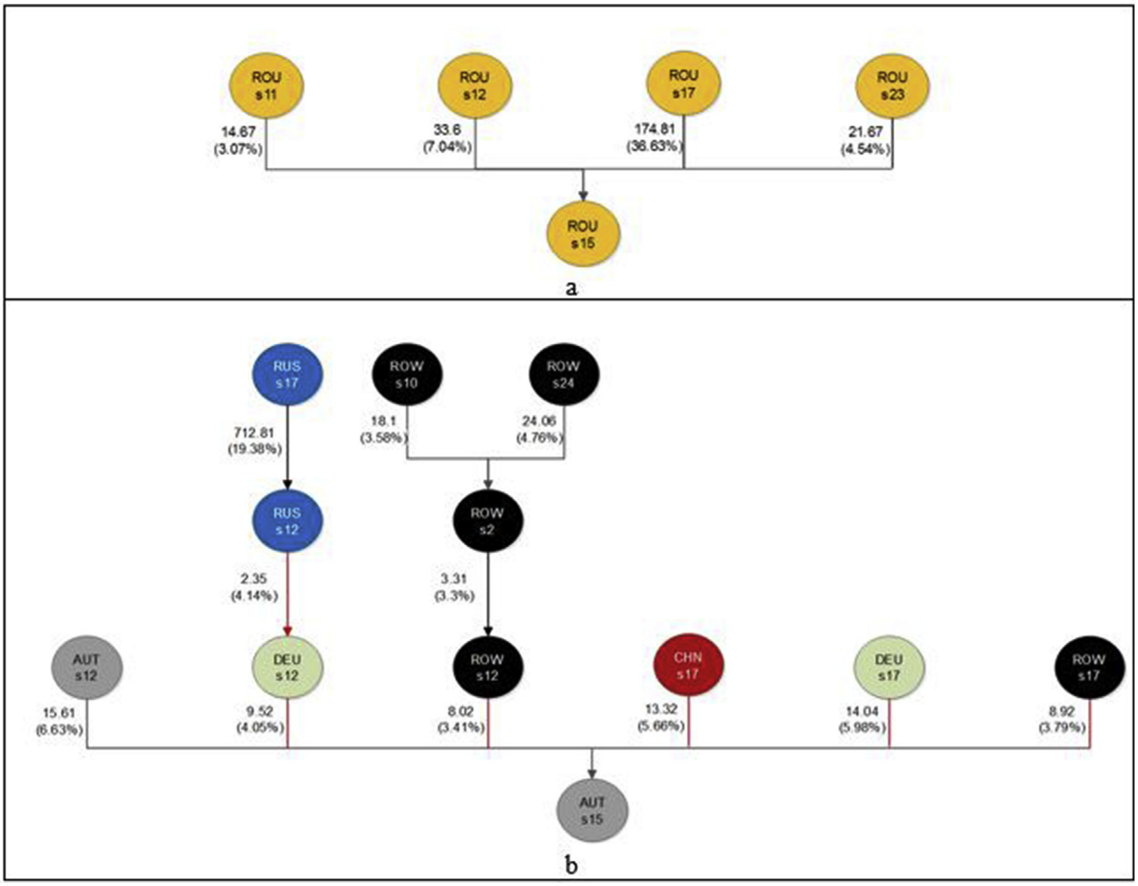

Fig. 11. GET for industry ROU_s15 (a) and AUT_s15 (b) computed for 2009. Legend: s2 – "Mining and Quarrying"; s10 – "Rubber and Plastics"; s11 – "Other Non-Metallic Mineral"; s12 – "Basic Metals and Fabricated Metal"; s17 – "Electricity, Gas and Water Supply"; s23 – "Inland Transport".

Table 6
Ten industries with the highest overall CO_2 intensity at the global level in 2009.

Country	Industry	Overall CO_2 intensity [Kg/$]
India	Electricity, Gas and Water Supply	16532.00
Estonia	Coke, Refined Petroleum and Nuclear Fuel	10965.95
China	Electricity, Gas and Water Supply	10578.29
Taiwan	Water Transport	8892.70
Indonesia	Electricity, Gas and Water Supply	8746.69
Taiwan	Electricity, Gas and Water Supply	8675.28
Russia	Electricity, Gas and Water Supply	7786.07
Estonia	Electricity, Gas and Water Supply	7761.80
Bulgaria	Electricity, Gas and Water Supply	7637.38
Taiwan	Mining and Quarrying	6226.86

and Water Supply" industry (AUT_s17) would reduce the overall emission intensity of industry AUT_s15 by 0.026%. In fact, industry AUT_s17 is not depicted in the GET since its contribution to the *overall CO_2 intensity* of industry AUT_s15 is lower than 3% (see the supplementary material).

5. Discussion

Nowadays the existence of increasing international trade resulting in globally interconnected production networks has completely modified the geography of CO_2 emissions. Therefore, tools monitoring CO_2 emissions at the global level and assigning responsibility for these emissions by overcoming the traditional territorial-based approach have been developed. This is required both to avoid any misinterpretation of the real environmental performance of a country and to design effective decarbonization strategies at national and global levels.

This paper contributes to this literature by referring to two accounting tools, i.e., the Global Emissions Chains (GECs) and The Global Emissions Trees (GETs), which adopt the consumer-oriented perspective and the global supply chain concept developed by Timmer et al. (2014). Both tools, which are based on the data provided by the MRIO tables (Timmer et al., 2015), are proposed in a new application, which quantifies the CO_2 emissions generated by one dollar of final demand of an industry in a given country along the entire global supply chain. In this way, the amount of CO_2 emissions associated with the final demand of the industry of the country can be then easily computed. According to this approach,

Table 7
Industry with the highest domestic CO_2 intensity for each country in 2009.

Country	Industry	Domestic CO_2 intensity [Kg/$]	Overall CO_2 intensity [Kg/$]
Australia	Electricity, Gas and Water Supply	5410.13	5478.83
Austria	Air Transport	863.93	1083.00
Belgium	Air Transport	2319.61	2653.15
Bulgaria	Electricity, Gas and Water Supply	7354.11	7637.38
Brazil	Water Transport	1676.95	1712.17
Canada	Electricity, Gas and Water Supply	2381.39	2419.02
China	Electricity, Gas and Water Supply	10498.41	10578.29
Cyprus	Electricity, Gas and Water Supply	3839.03	4341.39
Czech Republic	Electricity, Gas and Water Supply	3455.88	3591.30
Germany	Electricity, Gas and Water Supply	2164.31	2287.88
Denmark	Electricity, Gas and Water Supply	2101.88	2229.16
Spain	Other Non-Metallic Mineral	1186.53	1290.99
Estonia	Coke, Refined Petroleum and Nuclear Fuel	10696.05	10965.95
Finland	Electricity, Gas and Water Supply	2236.40	2420.88
France	Air Transport	1282.20	1446.63
Great Britain	Air Transport	3180.99	3272.15
Greece	Electricity, Gas and Water Supply	5376.35	5465.42
Hungary	Electricity, Gas and Water Supply	1504.55	1865.76
Indonesia	Electricity, Gas and Water Supply	8611.91	8746.69
India	Electricity, Gas and Water Supply	16403.72	16532
Ireland	Electricity, Gas and Water Supply	2189.68	2540.72
Italy	Electricity, Gas and Water Supply	1065.82	1388.19
Japan	Water Transport	1610.60	2059.04
South Korea	Electricity, Gas and Water Supply	5652.49	5937.02
Lithuania	Other Non-Metallic Mineral	1603.23	1890.25
Luxembourg	Other Non-Metallic Mineral	1137.53	1408.87
Latvia	Other Non-Metallic Mineral	1311.24	1642.15
Mexico	Electricity, Gas and Water Supply	4530.32	4678.75
Malta	Basic Metals and Fabricated Metal	3906.99	4218.04
Netherlands	Air Transport	2006.87	2312.65
Poland	Electricity, Gas and Water Supply	4845.41	5002.59
Portugal	Electricity, Gas and Water Supply	1618.23	1765.06
Romania	Electricity, Gas and Water Supply	3583.30	3850.52
Rest-of-the-world	Electricity, Gas and Water Supply	4414.09	4522.96
Russia	Electricity, Gas and Water Supply	7754.27	7786.07
Slovakia	Coke, Refined Petroleum and Nuclear Fuel	1463.48	2114.26
Slovenia	Electricity, Gas and Water Supply	2388.82	2611.56
Sweden	Water Transport	1398.74	1711.96
Turkey	Electricity, Gas and Water Supply	4075.98	4113.83
Taiwan	Water Transport	8678.12	8892.70
USA	Electricity, Gas and Water Supply	5345.19	5404.92

the sources of CO_2 emissions are identified and proper responsibility accounted to the industry of the country.

Both tools provide extended and focused analyses, useful for the development of effective decarbonization strategies. To this aim, specific indices are developed and their usefulness is shown.

In particular, it is shown that GECs offer the possibility to compute the CO_2 intensity directly and indirectly generated by an industry of a country to fulfill its demand and to distinguish between *domestic* and *foreign CO_2 intensity*. The degree of internationalization of a GEC can be also computed, so that for each country which sectors are exporters (importers) of CO_2 – i.e. industries with the degree of internationalization > (<) 0.5 – are found.

Furthermore, it is shown that comparing the GECs of different industries can provide useful information for policymakers. When comparing the same industry of different countries, the cleanest industry can be easily identified and its global supply chain identified. This can be used as a benchmark by industries in other countries to reduce their CO_2 emissions.

Note that extending the comparison to all sectors of all countries, the most pollutant sectors at a local and global level can be also found. For example, Table 6 displays the ten industries with the highest *overall CO_2 intensity* at the global level in 2009. Data show that the Indian "Electricity, Gas and Water Supply" industry is characterized by the highest *overall CO_2 intensity* in the world. The same industry in China, Taiwan, Indonesia, Estonia, and Bulgaria are in the top ten positions. This result is consistent with previous findings by de Vries and Ferrarini (2017), who recognize that the electricity production industry is responsible for more than 44% of global CO_2 emissions. This information can be useful for policymakers of global organizations for developing global effective decarbonization strategies.

Similarly, Table 7 shows for each country the industry with the highest *domestic CO_2 intensity* and the attendant *overall CO_2 intensity*. This information is useful for country policymakers interested to identify the most pollutant sectors in their country. This analysis suggests where specific actions should be targeted, such as, for example, for which sectors it is recommended supporting the development of cleaner technological processes. "Electricity, Gas and Water supply" industry is the most pollutant in terms of domestic CO_2 emissions intensity in many different countries, such as Australia, Bulgaria, Canada, China, Cyprus, Czech Republic, Germany, Denmark, Finland, Greece, Hungary, Indonesia, India, Ireland, Italy, South Korea, Mexico, Poland, Portugal, Romania, Slovenia, Russia, Turkey, and the USA. Another industry that is the most pollutant in several countries is the "Air Transport" industry (e.g., in Austria, France, and Gran Britain). Based on this, it can be argued that investing in greener technologies reducing the CO_2 emissions of these industries can determine a very high benefit for these countries.

Analyzing the evolution of the GEC of an industry of a country over time provides also interesting information. It permits to

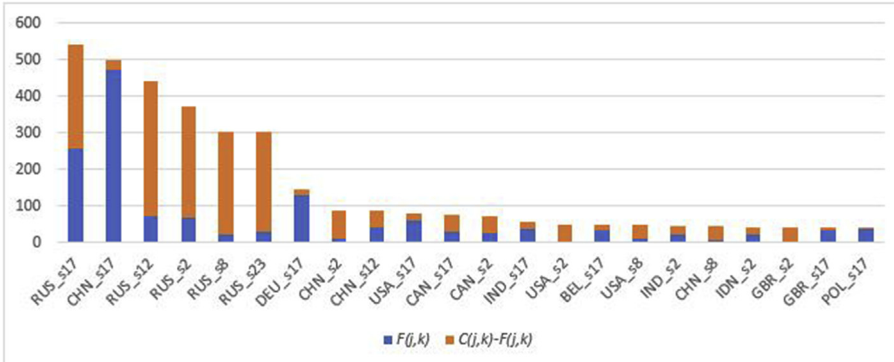

Fig. 12. F (j,k) and C (j,k) for the 22 industries with the highest C (j,k).

investigate the drivers of changes in the *overall CO_2 intensity* by assessing the effects of the change in CO_2 intensity of the sectors involved and the change in the structure of the global supply chain. It is shown how to apply the structural decomposition analysis to quantify both the effects. This analysis can be useful to assess if a country change in CO_2 emission intensity is due to technological innovation or change in the global supply chain. Our analysis for the Italian Transport Equipment highlighted that the sector has undergone decarbonization mainly due to a reduction of CO_2 intensity thanks to cleaner technologies. Furthermore, GECs can be used to analyze the environmental consequences of changes in the final demand of a given industry as well as the impact of final demand shifts. In particular, the effect in the shift of the final demand of the Italian "Transport Equipment" industry to China and France is quantified.

Furthermore, this paper proposes the GET, which offers a graphical view of the GEC. Focusing on the industries that are more relevant in percentage of the total CO_2 emissions, the GET provides a simplified graphical structure of GEC, highlighting industries mainly responsible for indirect CO_2 emissions of the root node as well as the interdependencies among industries.

Some indices based on the GETs are developed, useful to develop effective decarbonization strategies at national and global levels. In particular, we showed that the contribution coefficient, referring to the number of GETs where a specific industry is depicted, provides useful information for developing decarbonization strategies at the global level, while the national contribution coefficient, which focuses on the number of GETs of the country where the industry is depicted, is helpful for developing decarbonization strategies at the country level.

For example, in Fig. 12 the 22 industries with the highest contribution coefficient *C(j,k)* are shown with reference to 2009. The contribution coefficient of Russian "Electricity, Gas and Water Supply" industry (RUS_s17) is equal to 542, highlighting the importance of this industry for the CO_2 emissions at the global level. Furthermore, industry RUS_s17 belongs to the first level of 258 GETs: this means that this industry contributes by more than 3% of the global emission intensity of 258 world industries. It is also noteworthy that nine times the industries with the highest contribution coefficient concern the "Electricity, Gas and Water Supply" industry. These results confirm that decarbonizing such an industry is an important priority to reduce global CO_2 emissions. This in fact contributes to reduce emissions in many different industries and countries.

Similarly, GETs can support analysis at the level of the national economy. For instance, it is possible to compute GETs for all sectors of a given national economy and then discover the global industries that contribute at most to the CO_2 indirect production at the national level. Table 8 shows the values of *NC(j,k)* and *NF(j,k)* computed for Italy in 2009 and compares them with the same

Table 8
NC(j,k) and NF(j,k) for industries in Italy, Germany, and the USA.

ITALY			GERMANY			USA		
Industry	NC(j,k)	NF(j,k)	Industry	NC(j,k)	NF(j,k)	Industry	NC(j,k)	NF(j,k)
RUS_s17	34	6	**DEU_s17**	**33**	**33**	**USA_s17**	**34**	**32**
RoW_s17	34	31	RoW_s17	17	14	**USA_s2**	**28**	**2**
ITA_s17	**32**	**32**	CHN_s17	14	14	CAN_s2	27	1
RUS_s12	22	1	RUS_s12	8	0	CAN_s17	27	0
RoW_s2	22	1	RUS_s17	8	1	**USA_s8**	**27**	**11**
RoW_s10	22	0	**DEU_s12**	**7**	**7**	RoW_s2	27	1
RoW_s24	22	0	RoW_s2	7	0	RoW_s10	27	0
ITA_s8	**21**	**8**	RoW_s10	7	0	RoW_s17	27	1
RUS_s2	21	1	RoW_s12	7	1	RoW_s24	27	0
RUS_s8	21	0	RoW_s24	7	0	**USA_s23**	**13**	**11**
RUS_s23	21	0	RoW_s9	6	6	CHN_s17	10	10
ITA_s11	**19**	**17**	**DEU_s11**	**4**	**4**	**USA_s9**	**9**	**7**
ITA_s23	**19**	**19**	**DEU_s23**	**4**	**3**	**USA_s12**	**7**	**7**
CHN_s17	7	7	**DEU_s25**	**4**	**4**	**USA_s30**	**6**	**6**
ITA_s12	**6**	**6**	**DEU_s26**	**4**	**4**	**USA_s1**	**4**	**3**
RoW_s12	6	3	**DEU_s1**	**2**	**2**	**USA_s25**	**3**	**2**
ITA_s1	**3**	**3**	**DEU_s30**	**2**	**2**	**USA_s26**	**3**	**3**
ITA_s9	**3**	**1**	CHN_s2	1	0	**USA_s3**	**2**	**2**
ITA_s25	**3**	**3**	CHN_s12	1	1	**USA_s11**	**2**	**2**
RoW_s9	3	3	**DEU_s2**	**1**	**1**	**USA_s28**	**2**	**2**
ITA_s3	**2**	**2**	**DEU_s3**	**1**	**1**	**USA_s4**	**1**	**1**
ITA_s30	**2**	**2**	**DEU_s4**	**1**	**1**	**USA_s5**	**1**	**1**

values computed for Germany (one European country) and the USA (one not-European country) in the same year. For all these countries, the industry with the highest both *NC(j,k)* and *NF(j,k)* concerns “Electricity, Gas and Water Supply”. In fact, this industry is responsible for more than 3% of the *overall CO_2 intensity* of 32, 33, and 32 domestic industries in Italy, Germany, and the USA, respectively.

Interestingly, the impact of foreign industries on domestic CO_2 emission intensity can be highlighted. For example, Chinese “Electricity, Gas and Water Supply” industry (CHN_c17) contributes for more than 3% of the overall CO_2 emissions of 7 Italian industries, 14 German industries, and 10 American industries. Furthermore, differences among countries can be discovered. For example, the Rest-of-the-World “Electricity, Gas and Water Supply” industry (ROW_s17) contributes to more than 3% of the overall CO_2 emissions of 31 Italian industries and 14 German industries but only one American industry. Similarly, the domestic industry “Inland Transport” (s23) contributes to more than 3% of the overall CO_2 emissions of 19 Italian industries and 11 American industries but only three German industries.

6. Conclusions

In this paper, it was shown how GECs and GETs can be usefully adopted to analyze global CO_2 emissions focusing on single industries of a country and to develop effective national and international decarbonization strategies. However, the study presents some limitations. The tools proposed are based on data provided by WIOD database. MRIO tables require a huge amount of data to be collected, which currently are updated to 2009. This limits the possibility to provide update analyses until new data are collected. Furthermore, this methodology adopts input/output tables at a sector level rather at a product level. This means that the comparison among different GECs and GETs are made at the industry level. For example, the GECs of “Transport equipment” industry of different countries are compared in terms of CO_2 emission intensity to identify the benchmark industry. However, the different environmental performance of a sector in different countries could depend not only on the global supply chain and CO_2 intensity of involved sectors, but also on the goods and services produced by the sector in each country, which can be different. However, note that this is a limitation shared by all tools adopting the MRIO approach. The authors would like to stress that the proposed approach could be also applied with input-output tables at the product level. This will result in computing the GECs and the GETs of a product in a country. In such a case, the tools could provide even a more powerful analysis because more detailed comparisons could be done. For this reason, the authors suggest to put effort in developing databases computing tables at the product level so as to offer the possibility to make these interesting comparisons.

A further direction for future research could regard the development of monitoring tools where the *overall CO_2 intensity* is computed at the supply chain level. This information could be particularly relevant for sustainable supply chains, which globally compete on the market focusing on the environmental performance. In the same way, companies compute their carbon footprint, companies could quantify the *overall CO_2 intensity* of their supply network and communicate this information to stakeholders. The lower its value, the higher their reputation and the possibility to achieve a higher premium price from environmental-consciousness customers will be.

Appendix

Table 9
List of the industries considered by WIOTs.

Code	Industry
s1	Agriculture, Hunting, Forestry and Fishing
s2	Mining and Quarrying
s3	Food, Beverages and Tobacco
s4	Textiles and Textile Products
s5	Leather, Leather and Footwear
s6	Wood and Products of Wood and Cork
s7	Pulp, Paper, Paper, Printing and Publishing
s8	Coke, Refined Petroleum and Nuclear Fuel
s9	Chemicals and Chemical Products
s10	Rubber and Plastics
s11	Other Non-Metallic Mineral
s12	Basic Metals and Fabricated Metal
s13	Machinery, Nec
s14	Electrical and Optical Equipment
s15	Transport Equipment
s16	Manufacturing, Nec; Recycling
s17	Electricity, Gas and Water Supply
s18	Construction
s19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
s20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
s21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
s22	Hotels and Restaurants
s23	Inland Transport
s24	Water Transport
s25	Air Transport
s26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
s27	Post and Telecommunications
s28	Financial Intermediation
s29	Real Estate Activities
s30	Renting of M&Eq and Other Business Activities
s31	Public Admin and Defence; Compulsory Social Security
s32	Education
s33	Health and Social Work
s34	Other Community, Social and Personal Services
s35	Private Households with Employed Persons

Table 10
List of countries considered in the Multi regional input-output tables.

Abbreviation	Country
AUS	Australia
AUT	Austria
BEL	Belgium
BGR	Bulgaria
BRA	Brazil
CAN	Canada
CHN	China
CYP	Cyprus
CZE	Czech Republic
DEU	Germany
DNK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FRA	France
GBR	Great Britain
GRC	Greece
HUN	Hungary
IDN	Indonesia
IND	India
IRL	Ireland
ITA	Italy

(*continued on next page*)

Table 10 (*continued*)

Abbreviation	Country
JPN	Japan
KOR	South Korea
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MEX	Mexico
MLT	Malta
NLD	Netherlands
POL	Poland
PRT	Portugal
ROU	Romania
RUS	Russia
SVK	Slovakia
SVN	Slovenia
SWE	Sweden
TUR	Turkey
TWN	Taiwan
USA	United States
RoW	Rest of the World

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.06.297.

References

Arto, I., Dietzenbacher, E., 2014. Drivers of the growth in global greenhouse gas emissions. Environ. Sci. Technol. 48, 5388–5394. https://doi.org/10.1021/es5005347.

Caro, D., Bastianoni, S., Borghesi, S., Pulselli, F.M., 2014. On the feasibility of a consumer-based allocation method in national GHG inventories. Ecol. Indicat. 36, 640–643. https://doi.org/10.1016/J.ECOLIND.2013.09.021.

Caro, D., Pulselli, F.M., Borghesi, S., Bastianoni, S., 2017. Mapping the international flows of GHG emissions within a more feasible consumption-based framework. J. Clean. Prod. 147, 142–151. https://doi.org/10.1016/j.jclepro.2017.01.106.

de Vries, G.J., Ferrarini, B., 2017. What accounts for the growth of carbon dioxide emissions in advanced and emerging economies? The role of consumption, technology and global supply chain participation. Ecol. Econ. 132, 213–223. https://doi.org/10.1016/j.ecolecon.2016.11.001.

Dong, F., Yu, B., Hadachin, T., Dai, Y., Wang, Y., Zhang, S., Long, R., 2018. Drivers of carbon emission intensity change in China. Resour. Conserv. Recycl. 129, 187–201. https://doi.org/10.1016/J.RESCONREC.2017.10.035.

Duan, Y., Jiang, X., 2018. Visualizing the change of embodied CO2 emissions along global production chains. J. Clean. Prod. 194, 499–514. https://doi.org/10.1016/J.JCLEPRO.2018.05.133.

European Commission, 2011. Energy Efficiency Plan 2011 (Brussels).

Fernández-Amador, O., Francois, J.F., Oberdabernig, D.A., Tomberger, P., 2017. Carbon dioxide emissions and economic growth: an assessment based on production and consumption emission inventories. Ecol. Econ. 135, 269–279. https://doi.org/10.1016/j.ecolecon.2017.01.004.

IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York.

Jiang, X., Green, C., 2017. The impact on global greenhouse gas emissions of geographic shifts in global supply chains. Ecol. Econ. 139, 102–114. https://doi.org/10.1016/j.ecolecon.2017.04.027.

Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building eora: A global multi-region input–output database at high country and sector resolution. Econ. Syst. Res. 25, 20–49. https://doi.org/10.1080/09535314.2013.769938.

Leontief, W., 1986. Input-output Economics. Oxford University Press.

Liu, D., Guo, X., Xiao, B., 2019. What causes growth of global greenhouse gas emissions? Evidence from 40 countries. Sci. Total Environ. 661, 750–766. https://doi.org/10.1016/J.SCITOTENV.2019.01.197.

Malik, A., Lan, J., Lenzen, M., 2016. Trends in global greenhouse gas emissions from 1990 to 2010. Environ. Sci. Technol. 50, 4722–4730. https://doi.org/10.1021/acs.est.5b06162.

Meng, B., Peters, G.P., Wang, Z., Li, M., 2018. Tracing CO2 emissions in global value chains. Energy Econ. 73, 24–42. https://doi.org/10.1016/J.ENECO.2018.05.013.

Miller, R.E., Blair, P.D., 2009. Input – Output Analysis, Second. Cambridge University Press.

Mohlin, K., Camuzeaux, J.R., Muller, A., Schneider, M., Wagner, G., 2018. Factoring in the forgotten role of renewables in CO2 emission trends using decomposition analysis. Energy Policy 116, 290–296. https://doi.org/10.1016/J.ENPOL.2018.02.006.

Nguyen, H.T., Aviso, K.B., Le, D.Q., Tokai, A., 2018. Main drivers of carbon dioxide emissions in vietnam trajectory 2000-2011: an input-output structural decomposition analysis. J. Sustain. Dev. 11, 129. https://doi.org/10.5539/jsd.v11n4p129.

Peters, G.P., Hertwich, E.G., 2008. CO $_2$ embodied in international trade with implications for global climate policy. Environ. Sci. Technol. 42, 1401–1407. https://doi.org/10.1021/es072023k.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534, 631–639. https://doi.org/10.1038/nature18307.

Schmidt, S., Södersten, C.-J., Wiebe, K., Simas, M., Palm, V., Wood, R., 2019. Understanding GHG emissions from Swedish consumption - current challenges in reaching the generational goal. J. Clean. Prod. 212, 428–437. https://doi.org/10.1016/J.JCLEPRO.2018.11.060.

Springmann, M., 2014. Integrating emissions transfers into policy-making. Nat. Clim. Change 4, 177–181. https://doi.org/10.1038/nclimate2102.

The World Bank, 2017. World Bank open data [WWW document]. URL. http://data.worldbank.org/ accessed 5.29.17.

Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., de Vries, G., 2015. An illustrated user guide to the world input–output database: the case of global automotive production. Rev. Int. Econ. 23, 575–605.

Timmer, M.P., Erumban, A.A., Los, B., Stehrer, R., de Vries, G.J., 2014. Slicing up global value chains. J. Econ. Perspect. 28, 99–118. https://doi.org/10.1257/jep.28.2.99.

Tukker, A., Poliakov, E., Heijungs, R., Hawkins, T., Neuwahl, F., Rueda-Cantuche, J.M., Giljum, S., Moll, S., Oosterhaven, J., Bouwmeester, M., 2009. Towards a global multi-regional environmentally extended input–output database. Ecol. Econ. 68, 1928–1937. https://doi.org/10.1016/J.ECOLECON.2008.11.010.

UNFCCC, 1997. Kyoto Protocol to the united Nations framework convention on climate change adopted at COP3 in Kyoto, Japan, on 11 december 1997 [WWW document]. URL. https://www.eea.europa.eu/data-and-maps/indicators/primary-energy-consumption-by-fuel/unfccc-1997-kyoto-protocol-to. accessed 7.25.17.

United Nations, 2017. World Population Prospects. The 2017 Revision. New York.

Wang, H., Ang, B.W., Su, B., 2017. A multi-region structural decomposition analysis of global CO2 emission intensity. Ecol. Econ. 142, 163–176. https://doi.org/10.1016/J.ECOLECON.2017.06.023.

Wang, S., Zhao, Y., Wiedmann, T., 2019. Carbon emissions embodied in China–Australia trade: a scenario analysis based on input–output analysis and panel regression models. J. Clean. Prod. 220, 721–731. https://doi.org/10.1016/J.JCLEPRO.2019.02.071.

Wang, Z., Chen, S., Cui, C., Liu, Q., Deng, L., 2019a. Industry relocation or emission relocation? Visualizing and decomposing the dislocation between China's economy and carbon emissions. J. Clean. Prod. 208, 1109–1119. https://doi.org/10.1016/J.JCLEPRO.2018.10.166.

Wang, Z., Cui, C., Peng, S., 2019b. How do urbanization and consumption patterns affect carbon emissions in China? A decomposition analysis. J. Clean. Prod. 211, 1201–1208. https://doi.org/10.1016/J.JCLEPRO.2018.11.272.

Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecol. Econ. 69, 211–222. https://doi.org/10.1016/j.ecolecon.2009.08.026.

Wiedmann, T., Lenzen, M., Turner, K., Barrett, J., 2007. 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. 61, 15–26. https://doi.org/10.1016/J.ECOLECON.2006.12.003.

Xu, X., Mu, M., Wang, Q., 2017. Recalculating CO2 emissions from the perspective of value-added trade: an input-output analysis of China's trade data. Energy Policy 107, 158–166. https://doi.org/10.1016/J.ENPOL.2017.04.026.

Yan, J., Su, B., Liu, Y., 2018. Multiplicative structural decomposition and attribution analysis of carbon emission intensity in China, 2002–2012. J. Clean. Prod. 198, 195–207. https://doi.org/10.1016/J.JCLEPRO.2018.07.003.

Zhang, L., Liu, B., Du, J., Liu, C., Wang, S., 2019. CO2 emission linkage analysis in global construction sectors: alarming trends from 1995 to 2009 and possible repercussions. J. Clean. Prod. 221, 863–877. https://doi.org/10.1016/J.JCLEPRO.2019.02.231.

Zhu, B., Su, B., Li, Y., 2018. Input-output and structural decomposition analysis of India's carbon emissions and intensity, 2007/08 – 2013/14. Appl. Energy 230, 1545–1556. https://doi.org/10.1016/J.APENERGY.2018.09.026.

Zhu, Z., Puliga, M., Cerina, F., Chessa, A., Riccaboni, M., 2015. Global value trees. PLoS One 10, 10–12. https://doi.org/10.1371/journal.pone.0126699.