Nina Eisenmenger and Dominik Wiedenhofer and Anke Schaffartzik and Stefan Giljum and Martin Bruckner and Heinz Schandl and Thomas Wiedmann and Manfred Lenzen and Arnold Tukker and de Koning Arjan

Consumption-based material flow indicators - Comparing six ways of calculating the Austrian raw material consumption providing six results

Title: Consumption-Based Material Flow Indicators – Seven Approaches, Seven Results for the Austrian Raw Material Consumption

Article Type: Analysis

Authors Names:

Nina Eisenmenger[1*], Dominik Wiedenhofer[1], Anke Schaffartzik[1], Stefan Giljum[2], Martin Bruckner[2], Heinz Schandl[3], Thomas O. Wiedmann[4,5], Manfred Lenzen[5], Arnold Tukker[6], Arjan Koning[6]

*** Corresponding Author:** Nina Eisenmenger

contact details: Phone +43/1/5224000/408; email: nina.eisenmenger@aau.at

Affiliations:

[1] Institute of Social Ecology, Alpen Adria Universität Klagenfurt Wien Graz, Schottenfeldgasse 29, 1070 Vienna, Austria, nina.eisenmenger@aau.at

[2] Vienna University of Business and Economics, 1020 Vienna, Austria

[3] CSIRO Land and Water Flagship, Black Mountain, Canberra, ACT 2601, Australia

[4] School of Civil and Environmental Engineering, UNSW Australia, Sydney, NSW 2052, Australia

[5] ISA, School of Physics A28, The University of Sydney, NSW 2006, Australia

[6] Institute of Environmental Sciences (CML), Leiden University, P.O.Box 9518, 2300 RA Leiden, The Netherlands

Highlights

- RMC results diverge and range from 21 t/cap up to 33 t/cap
- 5 models calculate RMC to be higher than DMC, 2 result in an RMC lower than DMC
- the variation between the 7 RMC estimates is higher than the difference to DMC

- the RTB for biomass and non-metallic minerals changes from positive to negative
- both, DMC and RMC address important but different aspects of resource use

Abstract:

Understanding the environmental implications of consumption and production depends on appropriate monitoring tools. Economy-wide material flow accounting (EW-MFA) is a theoretically grounded method to monitor natural resource use and has been widely used in research and increasingly also policy programs. However, the increasing complexity of international supply chains requires the inclusion of indirect material use through international trade. The indicator raw material consumption (RMC) represents the material use associated with final demand no matter where on the globe material use occurs and thus provides a consumption based perspective next to the territorial focus of EW-MFA indicators. Several studies on RMC have been presented recently but with diverging results; hence, a better understanding of results is needed. This article presents a comparison of Austrian RMC for the year 2007 calculated by seven different approaches (4 multi-regional input-output (IO) and 3 hybrid life-cycle analysis-IO approaches). Five approaches result in an RMC higher than the territorial account for material use, i.e. domestic material consumption (DMC), two hybrid LCA-IO approaches calculate RMC to be lower than DMC due to a negative net-trade balance for biomass- and non-metallic minerals-based products. However, results diverge by 50% or even more for detailed material categories and the range of RMC results (12 t/cap) was thereby larger than any of the differences to the DMC (between –4 and +8 t/cap). Future research is required before a final decision about the most appropriate RMC calculations can be taken.
Finally, it has to be acknowledged that both the DMC and the RMC address important but different aspects of resource use and neither of these indicators is a perfect counterpart to GDP. With the different perspectives of DMC and RMC, a relation of the two to GDP, as it is done in resource productivity (or efficiency) indicators, provide some but different messages, which still need to be better understood (conceptually and methodologically).

Keywords:

raw material consumption; material footprint; material flow accounting; input-output analysis; sustainable resource use; resource efficiency.

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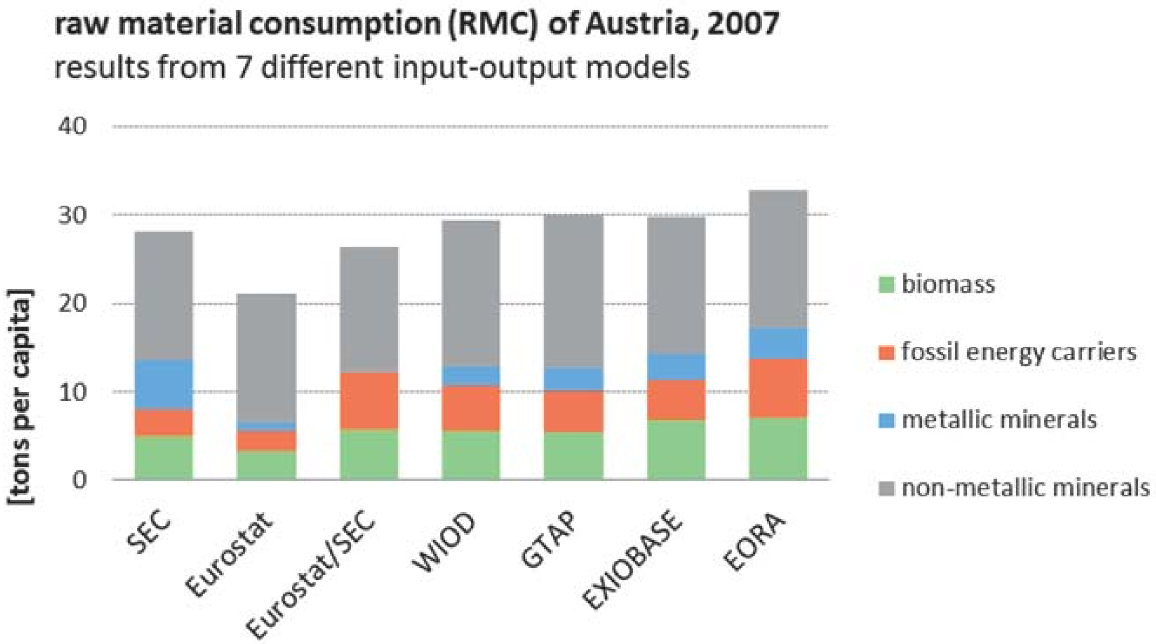

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contact details: Phone +43/1/5224000/408; email: nina.eisenmenger@aau.at

Affiliations:

[1] Institute of Social Ecology, Alpen Adria Universität Klagenfurt Wien Graz, Schottenfeldgasse 29, 1070 Vienna, Austria, nina.eisenmenger@aau.at

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[3] CSIRO Land and Water Flagship, Black Mountain, Canberra, ACT 2601, Australia

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Introduction

In recent years, material flow accounts (Eurostat, 2001; Fischer-Kowalski et al., 2011) have been expanded towards capturing the global material use associated with a nation's final consumption. These consumption-based accounts consider also the information on upstream material requirements of traded goods and derive an indicator for raw material consumption (RMC) (Weinzettel and Kovanda, 2009; Muñoz et al., 2009; Schoer et al., 2012a; Schaffartzik et al., 2014), recently also named material footprint (Schoer et al., 2012a; Tukker et al., 2014; Wiedmann et al., 2013). Such a consumption-based perspective on material use has also been called for in important policy papers (European Commission, 2011; OECD, 2011). In recent years, methods have been developed and results published for such an indicator (Muñoz et al., 2009; Weinzettel and Kovanda, 2009, 2011; Schoer et al., 2012a; Bruckner et al., 2012; Wiebe et al., 2012; Wiedmann et al., 2013; Schaffartzik et al., 2014; Tukker et al., 2014; Giljum et al., 2014). Comparative studies have been published for carbon and energy (Arto et al., 2014; Inomata and Owen, 2014; Moran and Wood, 2014; Weinzettel et al., 2014; Wiedmann, 2009a; Wiedmann et al., 2007), for land (Kastner et al., 2014), and one for RME (Schoer et al., 2013), which compares two calculation methods. With this research, we go one step further and provide a consistent comparison of all models used so far to calculate RME, i.e. seven different methods applied to the same country.

The method used to account for all materials used in a national economy is economy-wide material flow accounting (EW-MFA). EW-MFA is part of environmental accounts (Eurostat, 2014; United Nations, 2014) where special care was taken that environmental information systems complement national accounts in order to provide a consistent biophysical perspective in parallel to economic indicators such as the GDP. EW-MFA has been implemented in the European statistical reporting (European Parliament and the Council, 2011) and is included in the United Nations System of Environmental-Economic Accounting, SEEA (United Nations, 2014).

Domestic material consumption (DMC) is the most prominent indicator in EW-MFA and accepted as a headline indicator for resource use and resource efficiency (BM LFUW, 2012; European Commission, 2011). DMC is calculated as the balance of materials domestically extracted plus imports minus exports (Eurostat, 2012; Fischer-Kowalski et al., 2011). The physical volume of trade is accounted when crossing a national border. Usually, traded goods are at different stages of processing, wherefore the actual physical volume of traded commodities will differ from the mass of materials extracted to initially produce these traded goods. Economies specialized in the export of highly processed commodities can use imported primary or secondary products as material inputs into this production or can use materials which were domestically extracted and processed. If the latter type of production for export is dominant, DMC will be higher compared to the former as the mass of domestically extracted raw materials is larger than the mass of imported secondary goods. The indicator DMC illustrates the domestic (in the sense of territorial) material use of a national economy comprising all material flows entering an economy (either through imports or domestic extraction activities) and remaining there (i.e. not being exported). These materials may be transformed into stocks (including also materials fixed in investments), waste or emissions, or they may serve final consumption. DMC has a strong focus on the national economy and its production structure and is closely linked to national policy and legislation. It can also be interpreted as a waste equivalent (Weisz et al., 2006) since every material included in DMC becomes a waste flow and thus output to nature either in the same year or in future.

When assessing the materials globally required to satisfy domestic final demand, however, information is needed on the total material extraction, no matter where it occurs, which directly and indirectly fuels this final demand. The information on upstream material requirements of traded goods (i.e. the materials used to produce traded goods) is provided by the raw material equivalents (RME; Eurostat, 2001) of imports and exports and is then included in an indicator raw material consumption (RMC).

To date, calculations quantifying RMC use two main approaches: 1) a coefficients approach using data from life cycle inventories (LCI) to calculate upstream material requirements. In the context of EW-MFA, this approach was initially developed by the Wuppertal Institute in the 1990s, and applied mainly for the calculation of the Total Material Requirement (TMR) indicator (Bringezu et al., 2004;

Bringezu and Bleischwitz, 2009; Dittrich et al., 2012). 2) An environmentally extended input-output analysis (EE-IOA) approach employing information on the monetary structure of production and final demand to allocate direct as well as indirect upstream material requirements to final demand. EE-IOA has been applied to various resource use domains to account for upstream carbon and greenhouse gas emissions (Munksgaard and Pedersen, 2001; Peters, 2008; Hertwich and Peters, 2009; Davis et al., 2011), land requirements (Weinzettel et al., 2013; Yu et al., 2013), water (Daniels et al., 2011; Hoekstra and Chapagain, 2006; Hoekstra and Hung, 2005), a compound measure of Ecological Footprint (Ewing et al., 2012; Galli et al., 2013, 2012; Moran et al., 2013; Weinzettel et al., 2014; Wiedmann, 2009a), pressure on biodiversity (M. Lenzen et al., 2012), as well as in recent years also for material flows (Muñoz et al., 2009; Weinzettel and Kovanda, 2009; Wiebe et al., 2012; Bruckner et al., 2012; Kovanda and Weinzettel, 2013; Schoer et al., 2013; Wiedmann et al., 2013; Schaffartzik et al., 2014; Tukker et al., 2014; Giljum et al., 2014).

Within EE-IOA models, the calculation of upstream requirements of imports is a challenge because it requires information on the material use, production structures, and international trade relations of all trade partners. EE-IOA-based RMC accounts use different approaches to solve this problem: Single-Region IO Approaches (SRIO; Miller and Blair, 2009; Muñoz et al., 2009; Arnold Tukker et al., 2013b; Wood et al., 2009) apply the RME multipliers of domestic production derived from the IO model to all imports (commonly termed the 'domestic technology assumption', DTA). Other studies try to overcome the limitation of the DTA by combining the IO model with LCI-derived coefficients (hybrid LCA-IO approach; Suh, 2004) for those imported products that are not produced in the observed economy and thus are not represented in domestic IO multipliers. Multi-Regional Input-Output Models (MRIO; Tukker and Dietzenbacher, 2013; Wiedmann, 2009b; Wiedmann et al., 2011) link monetary IO tables from many economies or regions (the number of economies varies between MRIO models with mostly a relatively large 'rest of the world' aggregate) and in total cover the whole world-economy. Material extraction required to produce the traded goods and services is allocated to the country of final demand. To date, several studies have been published in which upstream material requirements were calculated. Some of them present results for single countries or regions

(Muñoz et al., 2009; Weinzettel and Kovanda, 2009; Schaffartzik et al., 2014), while others calculated RMC or material footprints for a large number of countries or aggregate regions covering the whole world (Bruckner et al., 2012; Tukker et al., 2014; Wiedmann et al., 2013).

This article presents an application of seven different approaches to calculate RMC to the same country, Austria, and for the same year, 2007, and by that aims at presenting the range of results that can be obtained by applying the currently available calculation methods for upstream material requirements. We employ three hybrid LCA-IO approaches and four MRIO approaches. After a short description of the different approaches, the results are presented and discussed for total RMC and four aggregate material categories. Finally, we compare RMC results to DMC and assess the relevance of both indicators for policy application.

Methods applied to calculate Austrian RMC

Most RMC calculations are based on monetary input-output tables, which depict the structure of the economy as intermediate inputs among industries and as final demand (including capital investment and exports) for the output of these industries. From these input-output tables, the so-called Leontief inverse, a matrix of multipliers which reflects the inputs required directly and indirectly to produce one unit of output of final demand (Miller and Blair, 2009), is calculated. The input-output model is extended with vectors for raw material inputs to each economic industry to calculate the material use associated with final demand. The following approaches were applied in this research:

1. **Hybrid LCA-IO approaches** use national IO tables but integrate LCI coefficients to provide multipliers for imported products which are not produced domestically and thus not represented adequately in the national IO structure. For this research, we used three hybrid LCA-IO approaches:
    - in the ***SEC*** approach we used a model developed by Schaffartzik et al. (2013), which uses the Austrian IO table and integrates coefficients from the GEMIS database (Öko-Institut, 2009) to cover the extraction and processing of materials for metal production (iron,

copper, aluminum), fertilizer production, and petroleum and gas extraction (Schaffartzik et al., 2013).

- in the ***Eurostat*** approach we used RME coefficients for imports and exports provided by Eurostat (Schoer et al., 2012a), which are based on a detailed European IO model (166 x 166 industries). Just as in Schaffartzik et al. (2013), Eurostat coefficients were developed by augmenting with LCI coefficients for metal products and products from fossil fuels. The coefficients derived from the European input-output structure represent European averages.
- in the ***Eurostat-SEC*** approach we combined the two approaches above. The Eurostat RME coefficients are used for imports and the resulting RME of imports are introduced into the SEC model to calculate RME of exports in order to use the information on the Austrian IO structure which differs from European averages.

2. **Multi-Regional Input-Output (MRIO) approaches** were developed to better represent foreign production structures (Tukker and Dietzenbacher, 2013; Wiedmann, 2009b; Wiedmann et al., 2011, 2007). An MRIO framework integrates domestic IO tables for all countries (or country groups) with trade matrices between all countries. MRIO models allow for a complete representation of global supply chains. An important attribute of MRIO models is that they are additive and closed at the global level, i.e. total global DE equals total global RMC. For our study, we used four MRIO approaches:

- The World Input-Output Database (WIOD, 2013) was developed in an FP7 European research project (Dietzenbacher et al., 2013; Timmer et al., 2012) and the publicly available version has a resolution of 35 industries and 40 countries.
- the Global Trade Analysis Project (GTAP, 2013); GTAP v5 and v8 (Narayanan et al., 2012) is the basis for an IO model used by Bruckner et al. (2012) which offers a high disaggregation for primary industries and provides data on 128 individual countries.

- EXIOBASE (exiobase, 2013) is a detailed MRIO model developed in two FP7 European research projects (Arnold Tukker et al., 2013a). EXIOBASE distinguishes 48 countries/regions, 163 industries and 200 products. The EXIOBASE 2.0 version of June 6, 2013 was used in the calculations.
- the Eora database (Eora, 2014; Lenzen et al., 2013; M Lenzen et al., 2012) integrates the national input-output data of 187 individual countries at a high level of resolution. The different national classifications and levels of sectoral aggregation are bridged with Eora-specific correspondence tables.

The hybrid LCA-IO approaches are very different from MRIO approaches, which is expected to have a significant effect on results. A comparison, however, is still valid because both approaches are used to calculate the same indicator, i.e. RMC, and derived resource efficiency indicators. More information on the different approaches and models is made available in the Supporting Information.

Error! Reference source not found. summarizes the main characteristics of the approaches used. The Eurostat-SEC approach is not listed because it combines the characteristics of the SEC and Eurostat approaches.

Table 1: Main characteristics of the seven approaches applied in calculating the RME of Austrian trade

		SEC	Eurostat	EXIOBASE	WIOD	GTAP	Eora
		(Schaffartzik et al., 2013)	(Schoer et al., 2012a)	(A. Tukker et al., 2013)	(Dietzenbacher et al., 2013; Timmer et al., 2012)	(Bruckner et al., 2012)	(Lenzen et al., 2013; M Lenzen et al., 2012; Wiedmann et al., 2013)
Approach		Hybrid LCA-IO	Hybrid mixed units LCA-IO	MRIO	MRIO	MRIO	MRIO
Regional resolution (no. of countries)		1 + DTA & LCA	1 + DTA & LCA	43 + 5 RoW	40 + RoW	128 + 3x RoW	186
Sectoral resolution		59	166	163	35	57	25-510
Resolution of	Biomass	3	16*	17	1	12	2-40

primary sectors for allocation of materials	Fossil fuel	1 / 1**	10	4	1	3	1-7
	Metal ores		18	8		3	1-8
	Non-metallic minerals	1	5	3		1	1-8
% of non-metallic minerals directly allocated to construction sector		50%	50%	0%	50%	50%	0%
Resolution of material extension (no. of material categories)		54	12	48	12	18	35

Legend: DTA = domestic technology assumption; RoW = Rest of the World; *16 of 20 are non-zero; **Due to data confidentiality, the 2007 Austrian IO table has an aggregated mining sector for oil, natural, gas and ores, and a sector for coal and peat.

Mining industries are aggregated differently in IO tables: the Austrian IO table aggregates mining of oil, natural, gas, and ores and thus materials like crude oil, extracted in large amounts (1 million tons) and at low prices, and like gold, used in small amounts measured in grams per capita and at high prices, in one industry. The extraction of coal and peat and the extraction of sand and stones form the other two mining sectors, respectively. WIOD aggregates all mining of abiotic materials in one industry. The other MRIO-based approaches report fossil fuel energy carriers, metals, and non-metallic minerals in separate industries, sometimes even more than one for each material category (see Table 1). Results presented below have to be understood in light of these differences in aggregation where higher aggregation is considered to cause less plausible results (Bouwmeester and Oosterhaven, 2013; Steen-Olsen et al., 2014).

Material flow data used for the calculation

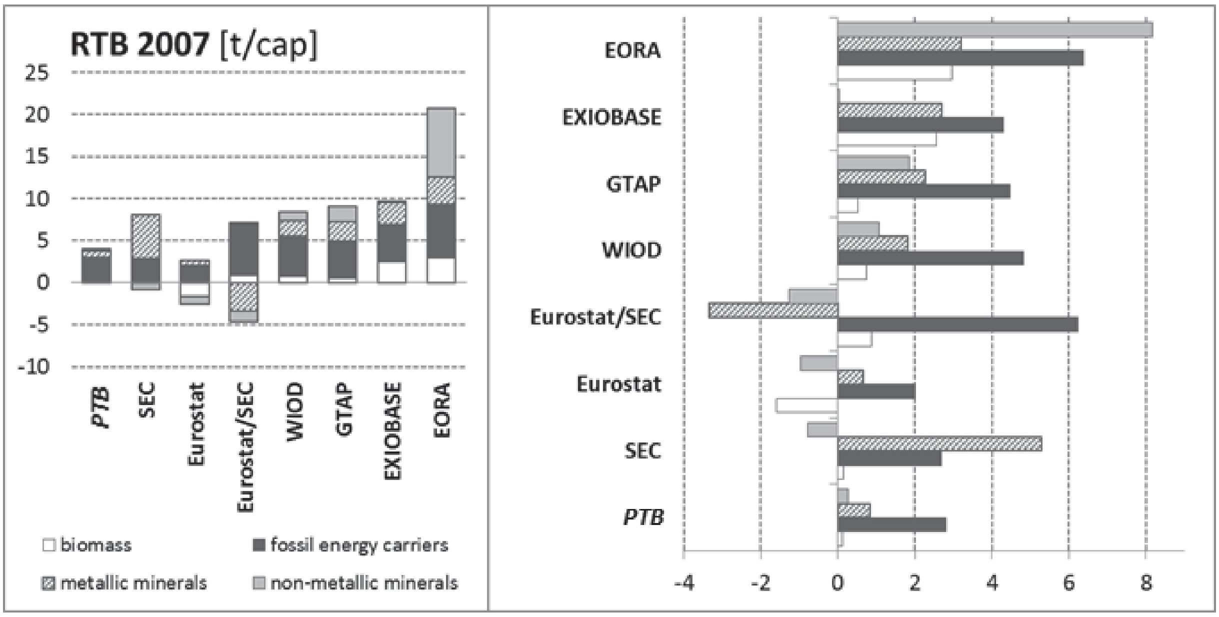
In RME accounts, the monetary IO models are extended by material extraction data (in the hybrid LCA-IO models also with physical imports) in order to calculate the RME of traded goods. Data on material extraction are part of the economy-wide material flow accounts (EW-MFA) framework, which include all materials extracted within a particular country as well as all physical imports and exports. Accounting methods and system boundaries are standardized and closely match the conventions of the system of national accounts (Eurostat, 2012, 2001; United Nations, 2014).

In all models employed for the calculation of RMC we used exactly the same material extraction data for Austria which is sourced from Statistics Austria (Statistics Austria, 2013). An exception to this is the Eora model where we used the MFA data already included in Eora, which is DE data from the CSIRO Global Material Flow Database (Wiedmann et al., 2013) for all countries including Austria. Compared to the DE of Statistics Austria the CSIRO data for Austria is lower (60%), especially for non-metallic minerals (SI for details). The MRIO models additionally contain DE data for all other countries or regions in the world. This data is either derived from www.materialflows.net (SERI, 2013) in the case of WIOD, GTAP and EXIOBASE and from the CSIRO Global Material Flow Database (Wiedmann et al., 2013) for Eora. The different sources for global DE are highly comparable and lie within a range of 6% (highest DE of 68 billion tons in Eora, lowest value of 65 billion tons in EXIOBASE; see SI for details). Highest deviations, i.e. 9%, are given for non-metallic minerals (lowest value of 28 billion tons in EXIOBASE, highest value of 30 billion tons in WIOD), whereas fossil energy carriers only differ by 1% or less (for a presentation of data see SI). With regard to trade, the three hybrid approaches used physical trade data from the Austrian EW-MFA (Statistics Austria, 2013). The MRIO approaches rely on monetary bilateral trade data to link national or regional IO tables (SI for details).

Raw material consumption (RMC) in Austria: Results and discussion

Austria's physical imports are higher than its exports, making the country a net-importer of global resource extraction. The physical trade balance (PTB = imports – exports; no upstream flows are included) amounted to 4 tons per capita (t/cap) in 2007; 70% of net-imports were fossil energy carriers, 20% were metal-based products. When upstream material requirements of trade are taken into account, net-imports increased considerably in all calculation approaches except for the Eurostat approach (**Figure 1**). The raw material trade balance (RTB = RME imports – RME exports = RIM – REX) is around twice as large as the PTB at 7.5 t/cap in the SEC model, 8.4 t/cap in WIOD, 9.1 t/cap in GTAP, and 9.6 t/cap in EXIOBASE. The results from the Eora model exceed all other calculations by far and with an RTB of 21 t/cap. In the Eurostat approach, the RTB is only 0.1 t/cap, which is lower than the PTB. This results from a negative trade balances for biomass and non-metallic minerals (see **Figure 1**). The Eurostat RTB being lower than the PTB implies that Austria is, considering all upstream requirements, supplying as many resources to the world as it consumes, suggesting that Austria's imports seem to be less material intensive than its exports.

Figure 1: Austrian raw material trade balance (RTB) in 2007 in tons per capita (t/cap) as calculated by seven different approaches



The coverage of RME flows usually differs in hybrid IO-LCA and MRIO approaches: Just as in EW-MFA, the RIM and REX calculated in hybrid LCA-IO include all biophysical imports and exports entering or exiting a country no matter whether these goods are destined for domestic final demand or for intermediate use. MRIO-based approaches, on the other hand, usually report as imports the raw material equivalents of domestic final demand which is not met by domestic production. Imports used in the production of goods and services for export are not included in the RIM of the country. RIM and REX in MRIO-based approaches can therefore be expected to be lower than those from EW-

MFA or hybrid IO-LCA (see **Figure 2**). In trade balances and also in RMC the differences balance out and thus these indicators can be compared between the different approaches.

Figure 2: Raw material equivalents of imports (RIM) and of exports (REX) for Austria in 2007 in tons per capita (t/cap) as calculated by seven different approaches

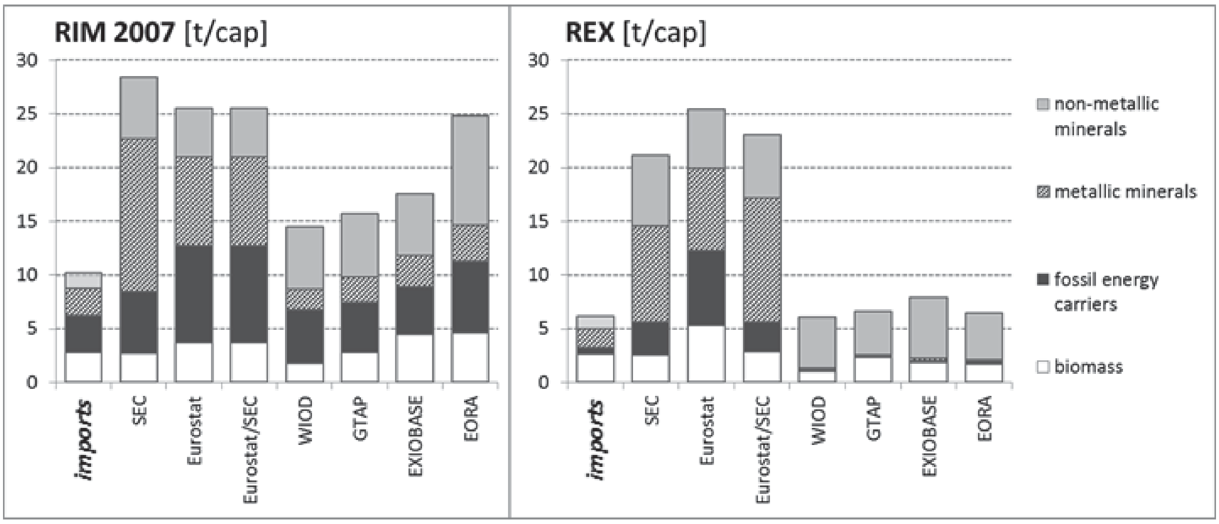


Figure 2 shows that REX from MRIO-based approaches are significantly lower compared to the hybrid IO approaches and mostly comprise biomass and construction minerals; metals and fossil fuels are not extracted in Austria in significant amounts.

Biomass materials

The physical amounts of biomass materials exported and imported by Austria are similar and net-imports are negligible at 0.1 t/cap in 2007. In Austria, agriculture and forestry are economically important. Extensive livestock systems in mountainous regions and the relative amount of grazed biomass (in t/GDP) is slightly higher than in most other European countries. In addition, Austria imports significant amounts of semi-manufactured biomass products, especially wood-based products and high-energy animal feed, which are further processed in paper production and livestock systems, and then exported (Eisenmenger et al., 2011).

The MRIO approaches all result in a biomass RTB that is higher than the PTB. EXIOBASE and GTAP have the highest disaggregation of biomass producing industries and products in their models (EXIOBASE differentiates 16 industries, GTAP 12 industries). However, the sequence of RTB results from low to high does not follow the disaggregation level of biomass-processing industries or biomass products (likewise described by Steen-Olsen et al. (Steen-Olsen et al., 2014, p. -) for CO_2 emissions): GTAP (0.5 t/cap) results in an RTB only slightly higher than PTB, whereas EXIOBASE delivers the second highest biomass RTB (2.6 t/cap). Eora's results are highest (3 t/cap). The result from WIOD (0.7 t/cap) is closer to the GTAP result.

The SEC hybrid approach arrives at 0.1 t/cap of biomass RTB; upstream flows of imports and exports are of similar size. The Eurostat (–1.6 t/cap) and Eurostat/SEC (–1.2 t/cap) approaches result in negative RTB values, turning Austria to be a net-exporter of biomass.

The Eurostat approaches result in biomass RTBs which are so different from those calculated under the other approaches that they raise questions about whether the Austrian production structure in agriculture and forestry is possibly not well represented by average European multipliers. Higher RIM and significantly higher REX in the Eurostat than the SEC approach (see **Figure 2**) may point to Austrian production structures being less input-intensive than the European average in monetary terms, translating to a lower material intensity as compared to average European production. The extensive livestock systems in Austria's mountainous regions are an example of this. The lack of disaggregation in the Austrian IO table with regard to biomass producing industries (agriculture includes livestock farming and is distinguished only from forestry and fishing as biomass-extracting industries) is another possible reason for the differences in results. In comparison to the EU average, Austria might be producing meat in extensive farming using a high amount of grazing while crop production might be less intensive than in other European countries and be associated with lower upstream requirements. Due to the high aggregation of primary sectors, however, both types of production are calculated to have the same upstream requirements per unit of output to final demand. Following our previous example, if meat with high upstream material requirements is mainly exported and crop products with relatively lower upstream material requirements meet domestic final demand, the material requirements of the former would be under- and of the latter over-estimated using average European multipliers.

A comparison between biomass RIM or REX and the respective trade flows from EW-MFA – which is for the above mentioned reasons only possible for the hybrid IOs – reveals that the SEC model calculates RIM and REX to be lower than the respective direct imports or exports. Mathematically, this is possible, if the product of the Leontief multiplier (L) and the price (exports[$]/exports[kg]) is smaller than 1, the RME of the exports will be smaller than the exports themselves. However, practically this is impossible because directly traded biomass goods by definition are included in the RME of imports and exports and therefore RIM and REX cannot be lower than direct trade. Also Marciai and Heijungs (2014) showed that a calculation of material footprints with Input-Output Tables can lead to a violation of the mass balance principle. Obviously, there are still issues to be solved in the application of physical flows to monetary IO models.

Fossil energy carriers

Austria does not extract significant amounts of fossil energy carriers but satisfies its demand through imports with a positive physical trade balance of 2.8 t/cap. The SEC and the two Eurostat approaches result in fossil energy carrier RTBs lower than the PTB (Eurostat: 2 t/cap, Eurostat/SEC 2.1 t/cap, SEC: 2.7 t/cap).

In the SEC model, fossil energy RIM are 1.7 times higher than imports; in the Eurostat approach RIM are 2.6 times larger than imports. Fossil energy REX are 5 times higher than exports under the SEC approach and 11 times higher under the Eurostat approach. The REX calculated with average European coefficients (Eurostat coefficients) results in 7 t/cap which is double the REX of the SEC approach (3 t/cap). The higher sectoral aggregation in the SEC approach may cause this difference. Furthermore, Austria has a higher share of hydro-power in domestic electricity production compared to other European countries and no nuclear power plants. The average European coefficients might not capture Austrian energy use structure well. In the SEC approach, upstream requirements of imports and exports are similar, and thus the RTB of fossil energy carriers of 2.7 t/cap is only slightly lower than the PTB (2.8 t/cap). The RTB in the Eurostat and the Eurostat/SEC approaches is lower than the PTB, implying that exports are more fossil fuel intensive than imports to Austrian final demand.

All MRIO approaches calculate the RTB of fossil energy carriers to be significantly higher than the PTB and higher than the RTB from hybrid LCA-IO approaches. EXIOBASE calculates 4.3 t/cap of fossil energy carrier RTB, GTAP 4.5 t/cap, and WIOD 4.8 t/cap. The highest RTB result comes from Eora at 6.4 t/cap. Since Eora and the SEC approach use the same IO table for Austria, the high difference in RTB of both approaches is due to higher upstream requirements associated with imports. Eora also calculates RIM to be 6.7 t/cap which is much higher than the other MRIO results, in which RIM amounts to values between 4.5 and 4.9 t/cap (see **Figure 2**).

Metallic minerals

Austria does not extract metal ores in significant amounts but relies on imports of metal goods. All approaches identify Austria as a net-importer of metal goods. The aggregation of Austria's low-level metal mining activities in only one sector does not represent the flows of metals and waste rock through the economy well. The hybrid IO-LCA models try to achieve more detail by using LCA coefficients as multipliers for imported metals.

The SEC approach (integrating 32 LCA coefficients for metals and metal products) results in the highest metal RTB, i.e. 5.3 t/cap. The Eurostat approach uses around 2500 LCA coefficients for metals and delivers the lowest RTB results (0.7 t/cap). The combined Eurostat/SEC approach results in 2.6 t/cap which is close to the MRIO results. The MRIO approaches deal with metals differently: WIOD aggregates metals, minerals, and fossil energy carriers into one sector and results in a metal RTB of 1.8 t/cap. Eora uses the Austrian IO table (one industry for metals and oil and gas) and thus applies the same domestic structure as the SEC model. Net-imports of metal ores in Eora sum up to 3.2 t/cap. GTAP takes a more detailed perspective and disaggregates the metal mining industry to three different industries. GTAP results in a metal RTB of 2.3 t/cap. With eight industries EXIOBASE has the most highly disaggregated IO table and calculates RTB to be 2.7 t/cap. The difference between the highest and the lowest estimated metal RTB is 4.6 t/cap.

The comparatively high RTB for metals in the SEC approach suggests that the applied LCA coefficients may lead to overestimation of the RME of imports. The application of LCAs to the macro level is often criticized for introducing potential for double-counting and for truncation of upstream requirement chains due to system boundary definitions (Suh et al., 2010; Reap et al., 2008; Suh et al., 2004). Additionally, the aggregation of all mining of all metals into one industry is likely to mean that the average distribution of all the outputs of this industry (including oil and gas) is unlikely to be equally appropriate for all types of metals (Bouwmeester and Oosterhaven, 2013). A detailed discussion of price inhomogeneity is provided by Weisz and Duchin (2006).

Non-metallic minerals

Non-metallic minerals cover materials such as sand, stones, and clays used for construction of buildings and transport infrastructure, which are extracted and used in bulk quantities, as well as minerals for fertilizer production or diamonds, which are used in small amounts at much higher average prices. Because of their comparatively low price per unit of mass, bulk construction minerals are hardly traded and they made up 50% of domestic extraction in the European Union at the beginning of the millennium (Weisz et al., 2006). Non-metallic minerals form part of the upstream requirements of many traded products through the use of infrastructure and building in the production and transport process of goods and the use of construction minerals therein. This use of construction materials is reflected in hybrid IO-LCA approaches through LCI coefficients but not in MRIO-based approaches; in the latter, expenditure on construction minerals corresponds to a capital investment and is therefore reported as a category of final demand. Other non-metallic minerals appear as upstream requirements in all accounting approaches. Fertilizers, for example, are an important upstream input into agricultural production.

In the case of Austria, half of the physical extraction of construction minerals is carried out by the construction sector (Eisenmenger et al., 2011; Milota et al., 2011; Schaffartzik et al., 2014). Therefore, the extraction of non-metallic minerals is allocated equally to the mining of sand and stones and the construction sector in all approaches except EXIOBASE and Eora, which follow a standard allocation of domestic extraction to primary industries (Table 1). The results of the Eora approach were additionally affected by the lower values for DE in the environmental extension compared to the other approaches (i.e. 7.5 t/cap instead of 15.4 t/cap, see SI).

The non-metallic mineral RTB especially reflects the fundamental difference in how physical inputs into building- and infrastructure-stocks, are accounted for under the hybrid IO-LCA and the MRIO-based approaches. Although the former approaches do account for these inputs within the production structure, assumptions have to be made in the use of LCI coefficients which significantly affect the results. Most significantly, choices must be made as to how construction mineral inputs into stocks are distributed both over time and for co-produced products to all of the outputs of each sector. Austria is a net-importer of non-metallic minerals with a PTB of 0.3 t/cap. Two models change Austria to a net-exporter, i.e. the Eurostat model (–1 t/cap), which delivers the lowest results for RTB, and the SEC hybrid IO model (–0.8 t/cap). EXIOBASE results in a balanced RTB (0 t/cap). All other models result in a positive RTB with Austria being a net-importer. Eurostat/SEC results in 1 t/cap, WIOD in 1.1 t/cap, and GTAP 1.9 t/cap. The Eora model calculates RTB to be 8.2 t/cap which is more than four times higher than GTAP as the next highest result. The high Eora results are especially due to high non-metallic RIM, which are more than twice as large as the other estimates. One possible explanation may be the allocation of non-metallic minerals in the Eora model exclusively to the mining sector while in all other approaches 50% of this material flow was allocated to the construction sector (Table 1). Additionally, also a potentially high aggregation of the mining industries in some IO tables in Eora (remember that Eora combines national IO tables with a varying number of industries, see Table 1) might cause misallocation along the supply chain.

Raw material consumption

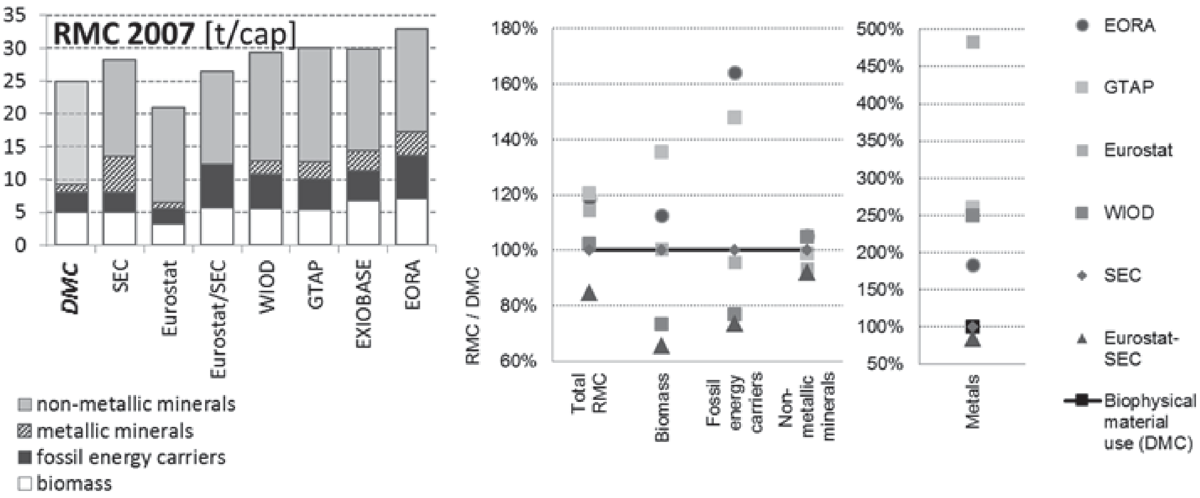
The most widely used indicator in standard EW-MFA is domestic material consumption (DMC = domestic extraction + PTB). The Austrian DMC was 25 t/cap in 2007. By replacing direct trade flows with RME, the indicator raw material consumption (RMC) (Muñoz et al., 2009; Weinzettel and Kovanda, 2009; Schoer et al., 2012b; Schaffartzik et al., 2014), also referred to as Material Footprint (Schoer et al., 2012a; Tukker et al., 2014; Wiedmann et al., 2013), is obtained. Among the seven approaches investigated here, the lowest RMC of 21 t/cap resulted from the Eurostat approach, while the highest RMC of 33 t/cap resulted from the Eora approach (

Figure 3). The range of RMC results (12 t/cap) was thereby larger than any of the differences to the DMC (between –4 and +8 t/cap).

GTAP and EXIOBASE arrive at an RMC of 30 t/cap, the SEC approach estimates 28 t/cap, WIOD 29 t/cap, and Eora 33 t/cap (see

Figure 3). Higher sectoral disaggregation, i.e. a larger number of sectors explicitly represented in the IO table, has been shown to enhance the interpretability of results (Miller and Blair, 2009; Lenzen, 2011; Bouwmeester and Oosterhaven, 2013; Steen-Olsen et al., 2014). WIOD uses the smallest number of sectors, followed by GTAP and then EXIOBASE, while Eora combines national IO tables with varying sectoral resolutions (Table 1). This hierarchy of sectoral detail does not directly translate to the same sequence in RMC results, where the RMC of GTAP and EXIOBASE is lowest, WIOD ranges in the middle, and Eora results in the highest RMC (see also Steen-Olsen et al., 2014 for CO_2 emissions).

Figure 3: Austrian raw material consumption (RMC) in 2007 in tons per capita (t/cap) as calculated by seven different approaches (left) and Austrian RMC as a share of DMC (RMC/DMC; right)



With the exception of the Eurostat result all approaches yield RMCs that are higher than DMC. But not enough information is currently available to verify whether the highest RMC estimate is more appropriate for Austria as an economy dependent on net-imports of many materials with high upstream requirements or whether a RMC only slightly higher than DMC better reflects the high export orientation of the Austrian economy in which revenues from exports account for over 50% of GDP.

Raw material equivalents are calculated to attribute global material extraction to the final demand in a country which it ultimately satisfies. The DMC indicator, on the other hand, represents a production perspective, accounting for all material used and transformed within national boundaries, minus physical exports. Weisz et al. (2006) interpreted DMC as ‘domestic waste potential‘ in that it measures those materials that will eventually become waste and emissions within the domestic territory. National policy or legislation can directly address DMC. RMC, on the other hand, measures upstream material requirements, no matter where they occur, required to satisfy domestic final demand, opening the perspective towards the global level. Material use activities outside the national economy cannot be addressed through national policies but through international trade policy, regulations and practices.

Both DMC and RMC have been related to GDP in order to report resource efficiency, i.e. the amount of GDP generated with one unit of material required. With the different perspectives of DMC and RMC, both relations to GDP provide some but different messages, which still need to be better understood (conceptually and methodologically); this particularly refers to the applicability as resource productivity indicator. While GDP includes final domestic demand and revenues from net exports in monetary terms; DMC includes domestic extraction and physical net-imports to reflect that in trade material and money flow in opposite directions, and RMC includes all global material extraction directly and indirectly required to meet monetary domestic final demand. While both the DMC and the RMC address important but different aspects of resource use, neither of these indicators is a perfect counterpart to GDP.

Conclusions

In this article we presented results from the calculation of RMC for Austria for the year 2007 based on seven different methods, i.e. three hybrid IO-LCA approaches, and four Multi-Regional Input-Output approaches. The seven approaches represent the most widely applied and recently published methods and models to calculate RMC (or Material Footprint). RMC results range from 21 t/cap up to 33 t/cap. With a variation of 12 t/cap (which is 30% of RMC or 50% of DMC) the difference is higher as compared to the difference between the DMC (25 t/cap) and the RMC. An analysis on the level of four material categories reveals that for two material categories, i.e. biomass and non-metallic minerals, not only the level but also the sign of the Trade Balance changes, turning Austria from being a net-importer to a net-exporter.

The calculations based on the SEC hybrid IO-LCA approach as well as the MRIOs WIOD, GTAP, and EXIOBASE show highest correspondence (only 1.6 t/cap difference between the highest and the lowest result). However, they still differ with respect to the composition along the four material categories. In the SEC approach metal ores make up for 70% of RTB, whereas in the three MRIOs 50-

60% of RTB are fossil fuels. The calculations based on the Eurostat coefficients deliver results that are significantly lower than the other results, both for the RTB as well as the RMC. EORA on the other hand delivers the highest estimates of RTB and RMC. The high RTB for non-metallic minerals is standing out not in total mass compared to the other material categories but also compared to the other approaches.

Our calculations made it possible, for the first time, to directly compare RME based indicators such as the Raw Material Consumption (also termed Material Footprint) or the Raw Material Trade Balance derived from different calculation methods. The results presented, provide a first overview of the deviation of results from different models. Despite the understanding gained, further analysis is still needed, though, in particular with regard to the impact of sectoral aggregation and the related high product and price inhomogeneity per sector in all approaches and with regard to allocation and truncation errors in the LCI coefficients in the hybrid LCA-IO approaches. A more in-depth analysis also has to consider the implications of different model assumptions. Quantitative uncertainty assessments, increased resolution of primary sectors and the interpretability of monetary allocation of biophysical resource use are seen as the main future research needs to improve RMC calculations. From the results presented, no clear preference for one method (hybrid IO-LCA) or the other (MRIO) can yet be drawn. Any decision has to take into account the different perspectives and needs among users, i.e. robustness, transparency, easiness to compile, temporal and spatial coverage and applicability, etc.

Finally, we discussed the two indicators DMC and RMC next to each other and showed their different but complementing perspectives. DMC represents a production or better territorial perspective which is also interpreted as “domestic waste potential”. Among the strengths of DMC is the easiness to compile, because DMC is based on standard national statistical data; DMC can also be directly addressed through national policy and legislation. RMC on the other hand is a consumption based approach, referring to the global material use required to satisfy domestic final demand. By that, RMC can address issues of global responsibility and a fair distribution of natural resources. With the different perspectives of DMC and RMC, a relation of the two to GDP, as it is done in resource productivity (or efficiency) indicators, provide some but different messages, which still need to be better understood (conceptually and methodologically). We even conclude that neither of the two indicators is a perfect counterpart to GDP.

Supporting Information

Specifications of the calculation models, material flow accounting indicators and data, and detailed RME results presented in data tables.

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