Increased carbon footprint of materials production driven by rise in investments

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The production of materials is an important source of greenhouse gas emissions. In order to reduce emissions, policies aim to enhance material efficiency and the circular economy but our understanding of the dynamics of material-related greenhouse gas emissions is limited. Here, I quantify the greenhouse gas emissions from material production and the carbon footprint of materials in industries that are the first users of materials, and in final consumption, using in a multiregional input-output model of the global economy and the hypothetical extraction method. From 1995 to 2015, greenhouse gas emissions from just material production increased by 120%, with 11 billion tons CO_2-equivalent emitted in 2015. As a proportion of global emissions, material production rose from 15 to 23%. China accounted for 75% of the growth. In terms of the first use of materials, two fifths of the carbon footprint of materials is attributed to construction, and two fifths to the manufacturing of machinery, vehicles, and other durable products. Overall, the replacement of existing or formation of new capital stocks now accounts for 60% of material-related emissions. Policies that address the rapidly growing capital stocks in emerging economies therefore offer the best prospect for emission reductions from material efficiency.

It is now widely acknowledged that material production causes over half of greenhouse gas (GHG) emissions from industry[1–4] and that material efficiency[5–7] and the circular economy[8–10] are important strategies to reduce those emissions. The International Energy Agency[2,11] traces energy use and direct emissions from production processes of high-volume materials—iron and steel, cement, chemicals and petrochemicals, aluminium, and pulp and paper. Not all materials are covered, emissions associated with non-energy inputs are ignored, and there is little information on the use of materials in the economy.[12] Individual technology case studies, for example, of buildings, infrastructure, and vehicles, show an important contribution of materials to the life-cycle impact of those systems and indicate potential synergies and trade-offs between energy and material efficiencies.[4,13] The lack of a comprehensive understanding may impair the development of material efficiency or circular-economy strategies for climate-change mitigation[12].

Here, I present a first analysis of the contribution of material production to the carbon footprint of products and final consumption between 1995 and 2015, analyze the use of materials by downstream fabrication and manufacturing processes, and quantify the global GHG emissions in the production of materials by type of material. On the basis of the system of national economic and environmental accounts, data on economic activity, energy and material conversion and use, and resulting emissions, researchers recently produced time series of multiregional input-output (MRIO) tables.[14–16] I used the method of hypothetical extraction (HEM)[17,18] to identify the contribution of materials in the upstream and downstream emission accounts of a global MRIO. The applicability of HEM to global MRIO tables has not been universally recognized.[19] In the section Methods and Data, I show that HEM is indeed applicable to global models and I provide a mathematical derivation of the determination of materials' contribution to the footprint of other products and final consumption. The assessment highlights the important contribution of materials that constitute the capital stock—machinery, factories, and warehouses—to the carbon footprint of produced products and delivered services, on the basis of a recently developed dataset for the endogenization of the consumption of fixed capital.[20] Finally, the investigation of different final-demand categories shows that capital formation is a more important final-demand driver than household or government consumption.

In conventional footprint analysis, double counting is a serious issue that impacts the usefulness of previous analyses, in particular for assessing the potential contribution of material efficiency to lowering the carbon footprint of products.[21,22] A recent proposal for correcting such double counting was developed in the process of quantifying the carbon footprint of Japan's material use[23,24] and was extended to analyze the environmental and employment impacts of global supply chains.[25] The present paper provides an independent derivation of the suggested method[23,25] to correct for double counting and extends it to downstream impacts. Following the material efficiency literature,[1–6] this manuscript addresses structural and functional materials used to compose products and excludes foodstuff, fuels, and chemicals.

GHG emissions from global material production

GHG emissions from material production increased by 120% from 5 billion metric tons CO_2 equivalent ($GtCO_2e$) in 1995 to 11Gt in 2015, raising their share of the global total from 15 to 23% (Fig. 1A). CO_2 equivalents are a metric for greenhouse gas emissions where the emissions of methane, nitrous oxide and other minor greenhouse gases are converted to an equivalent amount of CO_2 which would produce a comparable amount of climate forcing integrated over a 100-year time horizon. Iron and steel production caused 3.6 Gt CO_2e in 2011, the year with the most reliable data. When corrected for the use of materials in the production of other materials, this amounted to 31% (3.3 Gt) of all emissions caused by material production (Fig.1B, Table 1). The next most important contributions were from cement, lime, and plaster production with 24% and rubber and plastics including basic plastics with 13%. Non-ferrous metals contributed 10%, and non-metallic mineral products contributed 14%, with glass alone contributing 4% (Fig. ED1). Ignoring land-use-related emissions, including deforestation, pulp, paper, and wood products, caused a total of 1 Gt (9%). Of these materials, the largest growth in emissions was associated with glass; sand and clay; iron and steel; cement, lime and plaster; lead, zinc, and tin; and other non-ferrous metal products, which all increased by 160–170% in the period 1995–2015. The smallest growth was associated with paper, pulp, and wood products, stone, copper, and precious metals, but of all materials, only paper increased by less than the total global GHG emissions, 49%.[26]

In 2011, GHG emissions from the production of materials were 10.8 GtCO_2e. Of these emissions, 86% were CO_2, and the remainder was mostly methane associated with energy supply. Direct emissions from material-producing sectors constituted 53% of the cradle-to-gate emissions of the materials (Fig. 1A), a share that varied from 84% for cement to 11% for aluminium (Table 1a). Energy supply to material production and other upstream activities contributed 35% of the total, mining 2%, and other inputs 10%. Emissions associated with the production of fuel and electricity used in mining and of other inputs were counted as energy-sector emissions. If upstream energy were allocated to mining and other inputs, these would contribute 3 and 36% of emissions, respectively, emphasizing the importance of a life-cycle perspective when determining the emissions of material production.

GHG emissions associated with various uses of materials

The largest carbon footprints of materials in downstream production were those of cement, lime, and plaster in construction (2.5 $GtCO_2e$ in 2011) and of iron and steel used in manufacturing (2.4 Gt). Building and construction was the top designation for other non-metallic minerals including glass, as well as for wood, lead, zinc, and tin (Table 1b). Manufacturing was the top destination for rubber and plastics, aluminium, copper, precious metals, and other non-ferrous metals.

A more detailed breakdown reveals that iron and steel were used primarily in construction (a carbon footprint of 0.75 Gt CO_2e), in the production of machinery (1.1 Gt), for fabricated metal products (0.6 Gt), for motor vehicles (0.4 Gt), and for other transport equipment (0.2 Gt). Basic plastics corresponding to 0.5 $GtCO_2e$ were used in the production of rubber and plastics. Rubber and plastics were used in machinery, motor vehicle and other transport equipment, and final demand (ca. 0.2 Gt each).

When looking at the share of materials in the total carbon footprint of products delivered by different sectors of the economy, materials contributed 70% to the carbon footprint of construction (Table 2). High fractions were also obtained for electrical machinery and equipment (64%), machinery (60%), and other transport equipment (58%). Materials contributed 56% of the carbon footprint of vehicle production. Surprisingly, materials were important for the carbon footprint of some services, contributing 43% to real estate services, 37% to computer services, 34% to post and telecommunications, and 23% to recreational, cultural, and sporting organizations. For services, the use of buildings, equipment, and other capital goods were important channels for materials to contribute to carbon footprints. For example, materials in capital good contributed only 9% to the carbon footprint of construction but 27% to the footprint of post and telecommunications (Table 2). Table 2 contains a weighted global average multiplier of aggregated products, the share of direct emissions, and material and non-material inputs, identified as intermediate or capital inputs.

Final demand drivers of material production

The immediate demand of materials is often to produce semi-finished products and capital goods, which are then used further to produce consumer goods or services. The material-related footprint of the final demand for services, of the final demand for manufactured products, and of the net investment in additional buildings and infrastructure are 3GtCO_2e each (Fig. 2A). For services, material-intensive capital goods such as buildings and vehicles are more important than the intermediate input of materials to service production, as Table 2 shows. The final demand for food (0.6 Gt), energy (0.2 Gt), and transport services (0.2 Gt) was less important. Construction and machinery dominate investments, followed by vehicles and electronics. In consumption, services have grown to be important, especially public administration, health, and education.

The contribution of materials to the carbon footprint of consumption (and changes in stock and valuables) grew from 4.1 to 7.3 GtCO2e in the period 1995–2015, whereas their contribution to net investment grew fourfold from 1.0 to 4.2 Gt (Figure 2). The carbon footprint of gross capital formation, which includes all investment, grew from 3.6 to 9.4 Gt (Fig. ED3), surpassing that of consumption. Gross capital formation is the sum of net capital formation and reinvestment to replace capital which is being consumed (depreciated) in the process of production. Much of the increase in the total emissions from materials production is hence connected to a growth of net investment and the increasing importance of capital to industrial and service production.

Rapid growth in emerging economies

In 2015, slightly more than half of the emissions related to material production occurred in China (Fig. ED2a). China quadrupled those emissions from 1995, while India and Brazil almost tripled theirs. At the same time, the emissions in Canada, the European Union, Russia, and the United States declined by up to one quarter. Part of the explanation lies in trade. When looking at materials' contribution to the carbon footprint of countries consumption, only Russia saw a significant decrease, the EU saw a slight decrease (-4%), Canada saw an increase by 30%, and the US saw an increase by 9% (Fig. ED2b). As these post-industrial economies started importing more manufactured products, they also outsourced material production, primarily to China (Fig. ED2c). Net imports constituted one third of the material-related carbon footprint of the EU; net exports amounted to 13% of China's material-related emissions and 18% of the emissions from the BRITS (Brazil, Russia, Indonesia, Turkey, South Africa).

Three quarters of the dramatic increase in emissions happened in China. China's net exports rose moderately from 0.3 to 0.6 Gt and hence explains only a small portion of the growth. Instead, it is China's investment-driven development that serves as explanation for this rapid rise (Fig 2B): residential floor space increased from 10 to 30 m^2 per person,[27] and China built a first-rate high-speed rail network and constructed many roads, bridges, ports, and factories. Extending building lifetimes from 23 years to a more normal 60 years,[28] stopping building unoccupied flats,[29] and shifting from construction and heavy industry to services[30] can dramatically reduce material demand and its associated emissions. Light-weight designs[31] and low-carbon materials[32] offer GHG mitigation options for countries entering phases of rapid development, and improvements in reuse and recycling of materials have the largest applicability in developed economies, which have the largest stocks of manufactured capital.[33,34]

China had been moving towards a service economy and had increased its efficiency.[30] Emissions from cement production had stabilized. Current news, however, indicate that in light of the COVID19-induced slump in the world economy, China has stimulated investment again, resulting in a rising demand for iron ore on the world market. The overarching importance of the role of investment confirms Müller et al.'s[33] notion of infrastructure and durable goods as the main driver of material consumption and related GHG emissions, although the current analysis also shows that the stock is not necessarily static and that consumption still plays an important role. Similar build-ups of structures, transport systems, and factories are foreseeable in regions such as India and sub-Saharan Africa, where population growth is still rapid, and urbanization is at an earlier stage. Finding ways to urbanize and develop in a manner that relies on less materials and building lighter structures and collective transportation systems are potential approaches to reduce the material stock required for a modern society.[34,35]

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Author contributions

EGH designed the research, conducted the calculations, interpreted the findings, and wrote the manuscript.

Competing interests

The author declares no competing interests.

Figure captions

Figure 1: Greenhouse gas emissions from material production.

Three perspectives on the greenhouse emission of material production are shown: **(A)** by emitting process, **(B)** by class of material, and **(C)** carbon footprint of materials by using industry. Total emissions are measured in gigatons (petagrams) of CO_2 equivalent per year, represented by the black line, which refers to the right y-axis. The 100-year global warming potential was used to convert the climate forcing of greenhouse gases such as methane, nitrous oxide, and carbon hexafluoride into an equivalent forcing by CO_2.

Figure 2: The material-related carbon footprint of final demand.

The portion of the carbon footprint of final demand that has been caused by materials, organized by (**A**) product demanded and (**B**) country/region. Final demand consists of consumption (by households, non-profits, and the government) and net investment (gross fixed capital formation minus consumption of fixed capital). The regions represent the entire world; BRITS is Brazil, Russia, Indonesia, Turkey, and South Africa. EU is the European Union.

Methods and Data

Method choice. The present work utilizes input-output methods which have long been used to describe economic relations among sectors of the economy and have recently been shown to be useful for environmental analysis, especially when national tables are combined with trade data to construct a global table and when complemented by emission and resource-consumption data. Such multiregional input-output tables are now the preferred tools for material,[36,37] carbon,[38] and other footprinting.[39] Alternatively, life-cycle inventory data could be combined with material-consumption statistics to provide information on the impacts of various materials, as it has been done for the global use of metals.[40,41] Such an analysis could correct for double counting, and with material-flow analysis, it could be extended to the use of materials. It would be difficult to address the materials' contribution to the carbon footprints of final or materials' share of emissions in the carbon footprint of other products.

Data and scope. The modeling is based on version 3.6 of the EXIOBASE multiregional input-output (MRIO) database,[14,42] in which different materials were detailed on the basis of data from mineral statistics[43,44] and IEA energy statistics.[45] EXIOBASE 3.6 represents the world economy in 43 individual territories and 6 aggregated regions. CO_2 emissions from fossil fuel combustion and industrial processes such as iron and clinker production, methane emissions from agriculture and the energy system, and nitrous-oxide emissions from agriculture are the most important sources of GHG emissions. Emissions from land-use change were not included, because they cannot be clearly allocated to a specific production activity, and CO_2 absorption in the growth of wood or through the carbonation of cement was ignored.[46] These omissions result in potential errors connected to wood, pulp, and paper and an overestimate of the climate impact of cement and plaster.

The production and the consumption of up to 200 products are modeled in each region, including the following materials: Iron and steel; Aluminium; Copper; Precious metals; Lead, zinc and tin; Other non-ferrous metals; Cement, lime, plaster; Stone; Sand and clay; Other non-metallic minerals; Glass; Wood; Pulp; Paper; Rubber and plastic, Basic plastics. Note that this is a product-by-product table; therefore, inputs are to production processes, not economic sectors. The material-efficiency work by the IEA,[11] by comparison, addresses iron and steel, aluminium, cement, pulp and paper, and chemicals. It specifies energy use but does not quantify related or other upstream emissions. Other MRIO tables do not offer the level of detail on different materials presented here, and plastics are commonly grouped with other chemicals. Further, data on the consumption of capital are not available, making it impossible to carry out the modelling presented here without more data development.

Endogenization of capital. The use of capital goods such as machinery, buildings, and vehicles in the production of goods and services was included in the carbon-footprint assessment by using the approach and data in Södersten et al.[20] In this methodology, the consumption of fixed capital is treated as an input to production, with the required material demands, whereas the gross fixed capital formation, which normally is treated as a category of final demand, is replaced by the net fixed capital formation, reflecting only the investment above the consumption of fixed capital, which can be seen as expanding production capacity. In this manner, the carbon footprint of a product includes the emissions associated with producing the machinery used in the product's production. The annual table is still balanced and reflects the annual emissions, including those of material production. However, the disadvantage of this approach is that the technology assumed to be used for producing the capital goods is the current technology, their "carbon replacement value,"[33] and not the likely higher historical costs. Alternative approaches in which emissions associated with current capital formation are allocated to future years of capital utilization could remedy this problem[47] but do not yet offer the same capital product detail utilized here. To investigate the importance of gross fixed capital formation, the carbon footprint of gross fixed capital is also calculated (Fig. ED3), with the total material-related carbon footprint of final consumption plus investment covering emissions from material production in that year plus a representation of emissions of the previous years associated with the capital consumed in the production of materials in the given year.

Input-output methods. In an input-output table, the matrix *A* of input coefficients describes the technology of the economy, with each column representing the intermediate inputs required to produce a unit output of a product. The matrix *Y* represents the final demand for products, and the vector *x* represents the production volume. The market balance in a closed or global economy shows that the total output needs to satisfy both the required intermediate inputs and the final consumption, $Ax + Yi = x$, where *i* is a vector of ones that sums over the preceding matrix. This system of linear equations written in matrix notation can be solved for the total production volume, yielding the Leontief demand-pull model, $x = (I - A)^{-1}y = Ly$, where y is an arbitrary unit of final demand. *L* is the Leontief inverse, which specifies the production volumes per unit final demand from each sector.

The matrix or row vector π represents the input of production factors (or value added), such as capital, labour, and land, to produce a unit output in each sector. Together, A and π represent the technology of the economy. The firm or production balance indicates that the price of each product is the sum of the costs of intermediate inputs and the costs of factor inputs, or the value added, per unit output. Writing this for each production process gives $pA + \pi = p$. Solving for the price of goods, we obtain the Leontief price model, $p = \pi(I - A)^{-1} = \pi L$.

The emissions per unit output are contained in the matrix *S* (one line per pollutant) and are weighted with the characterization vector *c* of 100-year global-warming potentials to obtain CO_2 equivalent. The Leontief demand-pull model can be used to calculate the carbon-footprint multiplier, that is, the cradle-to-gate GHG emissions to produce one unit of each product, $m = cSL$. Note the similarity between the multiplier for emissions and the price. The total carbon footprint of a final consumption basket y is given by $E = cSLy$. If y only describes final consumption, there is no double counting, because all emissions are allocated to final consumption.

This Leontief demand approach to the quantification of the cradle-to-gate environmental impacts and carbon footprints is widely accepted and can be applied to any final product.[15,16] It could, in principle, also be applied to the materials in question. However, materials are required to produce materials. In fact, there is very little final demand for materials; the final demand is for products, including machinery and structures, made from materials and services created with the help of these products. Accounting only for materials purchased by final consumers would grossly underestimate the importance of materials for GHG emissions. An application of the total Leontief multiplier to gross output (i.e., total material production) does not yield the proper total environmental impacts[22] because of double counting.[21,22] The hypothetical extraction method (HEM)[17,48,49] offers a way in which the economy-wide impact of material production (or any other intermediate inputs) can be estimated exactly while avoiding double counting. It does so by quantifying the production volumes and emissions not related to material production and by identifying the production activities and emissions related to materials as the remainder.

HEM is used in regional and structural economics to study forward and backward linkages among sectors, as well as the potential economic consequences of disasters and acts of terror.[17,18,48,50] Recently, Dietzenbacher, von Burken, and Kondo[19] argued that HEM cannot be used in global models, because the extracted product is often seen as being imported (e.g., see Duarte et al.[18,50] as well as Fig. ED4), and there is no place from which to import in a global model. The following section shows that HEM can be applied broadly to any system for which the basic input-output accounting identities and Leontief production functions hold. The extraction of a sector is only hypothetical and provides an identification of relationships within the input-output table. By implication, it also applies to global and multiregional models, where any number of production processes, individual inputs, or a fraction thereof can be extracted.

Hypothetical extraction method. We would like to quantify the use of various production processes x^o in the economy required to satisfy both the intermediate and final consumption of a specific product, or group of products, signified by *o*. Further, we would like to quantify the use of factors in the production of those goods, and the share of the cost/factors of producing *o* in the price/factor requirements of other goods. Imagine now that we engage in an experiment where we trace the expenditure on *o* through the value chain by splitting the input-output description of the economy into two additive parts: one describing the complete production of intermediate and final demand for products *o*, including the production of products $* \notin o$ serving as intermediate input to the production of *o,* and the other describing the final demand for the remaining products * (Fig. ED4),

$$A = A^* + A^o; y = y^* + y^o \quad (1)$$

where the production volume *not* involved with the production of *o* is given by

$$A^*x^* + y^* = x^* \quad \rightarrow \quad x^* = (I - A^*)^{-1}y^* = L^*y^* \quad (2)$$

The Hypothetical Extraction theorem says that the output required to satisfy the intermediate and final demands for the extracted product, *o*, can be calculated as the difference in the production volume of the unperturbed system and the system where certain intermediate and final demand has been extracted.

$$x^o = Ly - L^*y^* \quad (3)$$

Alternatively, the value can be identified as

$$x^o = Ly^o + LA^oL^*y^* \quad (4)$$

and the two solutions can be shown to be equivalent because $LA^oL^* = L - L^*$. The identification of the production volume of extracted materials through eq. 4 corresponds to the identification of sectors by Cabernard et al.[25] based on the work of Dente et al.[23] It can be seen from eq. 3 that HEM avoids double counting.

The production balance eq.5a can be used to identify the contribution of the extracted products to the price of the non-extracted products (Fig. ED4). It can be solved using the solution to the production balance of the extracted products $p^o = \pi^o L$.

$$p^* = p^* A^{*\cdot} + p^o A^o + \pi^* \qquad (5a)$$

$$p^* = \pi^* L^* + \pi^o L A^o L^* \qquad (5b)$$

Here, the second term of the right-hand side of Leontief price model in eq. 5b represents the value added associated with producing the extracted inputs, i.e. the materials. For (1) and (2) to hold, $p^o = p^* = p$ and $\pi^o = \pi^* = \pi$. Given that emissions and other factor inputs can be treated in the same manner as the value added, the carbon footprint of material production in other products (y*) is given by the multiplier

$$m^o = sLA^o L^* = s(L - L^*) \qquad (6)$$

Here s = cS, the GHG emissions in CO_2 equivalents per unit output.

To determine the total emissions associated with the production of extracted inputs, there are now two ways of calculating those. One is simply to multiply the production volume required to produce the extracted product by the respective factor coefficients.

$$E^o = sx^o \qquad (7a)$$

The second is to sum the respective multipliers over the final demand for extracted and non-extracted products.

$$E^o = sLy^o + sLA^o L^* y^* \qquad (7b)$$

The respective vector and matrix multiplications entail summations over contributions of different producing processes, trades, and final demands. It is of interest to distinguish these through a decomposition of the matrix multiplication. Γ symbolizes the decomposition of the total factor costs of producing the extracted product, here, the carbon footprint of materials.

$$\Gamma^{x} = s\widehat{x^{o}} \quad (8)$$ by emitting process (Fig. 1A, Table 1a)

$$\Gamma^{FU} = sL\widehat{y^{o}} + sLA^{o}\widehat{x^{*}} \quad (9)$$ by first use (Fig. 1C, Table 1b)

$$\Gamma^{y} = sL\widehat{y^{o}} + sLA^{o}L^{*}\widehat{y^{*}} \quad (10)$$ by product in final consumption (Fig.2, Table 1c)

$$\Gamma^{M} = \widehat{m}y^{o} + \widehat{m}A^{o}L^{*}y^{*} \quad (11)$$ by material (Fig. 1B)

Here, the entire production of material(s) *j* was extracted by setting all intermediate and final demand for both domestically produced and imported inputs to other sectors and the final demand to zero ($A^{*}_{j,\cdot} = 0; Y^{*}_{j,\cdot} = 0$). As Dietzenbacher and Lahr[17] have shown, it is not necessary to set cells to zero, through partial extraction; one can also set them to a different value. One can also extract only a single input, such as the use of steel in the automotive industry, as long as eq. 1 holds.

The identification of individual materials. If a single material is extracted, other materials will have been used in its production, for example, steel and copper in the machinery and cement in the infrastructure. Some materials are intermediate stages to other materials, such as pulp for paper production. If all materials are extracted individually, the total emissions obtained by summing over the E^{o} for all materials will thus contain double counting. The next paragraph describes a strategy to identify such interdependencies. To avoid double counting and correctly estimate the emissions associated with each material going to the production of downstream products and apart from the inputs of other assessed materials, eq. 11 was used for the case where all materials have been extracted at the same time. The calculation method implies that emissions during the production of zinc used as a steel alloy are counted as being part of the carbon footprint of steel, not that of zinc, and the carbon footprint of zinc is only for zinc used outside material production.

Interdependencies of different materials (Table S1). To determine the use of materials as direct or indirect inputs in the production of other materials, a single line was added to the extension matrix S for each material *j*, being unity for each production process of the respective material and zero otherwise. With this S, equation (8) then yields the amount $\lambda_{ij}$of materials *i* required to produce each individually extracted material *j* and λ_{ii} is the production volume of material *i*. Table S1 contains the results for all materials. It displays interdependencies, such as the use of most pulp for paper production or the use of nearly half of basic plastics in rubber and plastic production. For most materials, on the order of 10–20% of the production volume is used in the production of materials.

The analysis was conducted at the country/regional level, with each material being extracted in all regions at once, and the results were aggregated to the global level.

Uncertainty. The present assessment of the carbon footprint of materials, the use of materials, and the material-related component of the carbon footprint relies on a multiregional input-output table constructed for this type of analysis. Different MRIO tables have been constructed by using different principles and data sources, yielding different results in footprint studies.[51] Significant sources of uncertainty are related to the assumed homogeneity of products or sectors and related to that, the aggregation of products,[52] and the uncertainty in the emissions data. By using a Monte Carlo analysis of country-level consumption-based carbon-emission accounts across different MRIO databases, Rodrigues et al.[53] find a coefficient of variation (CV, normalized standard deviation) of 2–16% across countries. They find much higher product-level uncertainty ranging from 10 to 200%, depending on the product. Similar uncertainties apply to the results reported in this manuscript, with higher relative uncertainties for smaller production volumes. We cannot necessarily assume that the uncertainties of individual-country products are independent from each other; there may be issues associated with the collection of energy-use data or the disaggregation procedure which afflict all estimates for a specific material in the same manner.[53] Uncertainties for the most recent years are higher than those up to 2011; indeed, the input-output tables were detailed on the basis of a set of assumptions and preliminary data, because final national-account data were not yet available.

Nuss and Eckelman[40] projected the carbon footprint of global metal consumption in 2008 by using life cycle assessment (LCA) data and global production volumes of metals. They estimated 3.1 $GtCO_2e$, compared to 3.7 estimated in this work. The contribution of iron and steel, aluminium, and other metals was 2.4, 0.4, and 0.3 Gt, respectively, compared to 2.8, 0.5, and 0.4 in the present paper. Although the widely acknowledged issue of cut-off errors in LCA would offer a convenient explanation, there can be many other causes for this discrepancy. Yet the comparison provides some comfort that the first significant figure is correct.

Data availability

A public version of EXIOBASE 3 is available on Zenodo, https://doi.org/10.5281/zenodo.3583071. The public version differs slightly from the version that was used in the present research, which makes use of proprietary third-party energy data from the International Energy Agency (IEA). The private version of the data is available from the author upon request by anybody who has obtained a license to the IEA Energy Statistics and Energy Balances.

Code availability

MatLab code is available on Zenodo, https://doi.org/10.5281/zenodo.4280697

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Tables

Table 1: Cradle-to-gate emissions of greenhouse gases associated with the production of materials in 2011. The share is always the share of total emissions shown in the top line. Emissions are split by (a) location where emissions occur (similar to scope 1, 2, and 3 in the Greenhouse Gas Protocol), (b) the sector buying the materials (first user), and (c) the final product that consumers purchase or companies invest in.

	Iron & steel	Aluminium	Other metals	Cement	Glass	Other minerals	Wood products	Plastic & rubber
GHG emissions (Gt CO_2e)	3.3	0.58	0.49	2.6	0.42	1.0	0.97	1.4
(a) Location of Emissions								
Material production	48%	11%	28%	84%	25%	42%	33%	10%
Energy	38%	62%	33%	12%	48%	38%	39%	57%
Mining	2%	2%	13%	1%	2%	10%	1%	1%
Products and services	12%	25%	26%	3%	25%	10%	27%	33%
(b) Use of Materials by Industry								
Construction	23%	5%	25%	94%	37%	70%	20%	10%
Machinery, incl. electrical	32%	47%	32%	0%	10%	4%	3%	14%
Fabricated metal products	19%	19%	16%	0%	3%	1%	1%	2%
Transport equipment	14%	10%	3%	0%	8%	2%	2%	12%
Electronics	2%	5%	5%	0%	6%	1%	3%	8%
Other products	3%	10%	9%	1%	18%	7%	32%	25%
Services	2%	1%	3%	2%	11%	5%	19%	11%
Final Consumption	4%	3%	7%	2%	7%	10%	21%	17%
(c) Carbon footprint of Materials in Final Consumption and Net Capital Formation								
Food	5%	5%	5%	4%	9%	4%	11%	8%
Clothing	2%	2%	2%	1%	2%	2%	3%	4%
Shelter	3%	3%	3%	3%	2%	3%	6%	4%
Construction	23%	16%	27%	49%	32%	43%	10%	10%
Transport equipment	11%	10%	6%	2%	6%	4%	3%	9%
Machinery, incl. electrical	15%	20%	14%	2%	6%	6%	3%	7%
Electronics	4%	5%	5%	2%	5%	3%	3%	5%
Other manufactured products	7%	9%	8%	3%	6%	4%	23%	21%

Public adm., health, education	15%	16%	15%	15%	17%	16%	22%	18%
Real estate services	6%	6%	6%	8%	6%	6%	5%	5%
Transport services	3%	2%	2%	3%	2%	2%	2%	2%
Other services	8%	8%	7%	9%	7%	7%	9%	8%

Table 2: Sale-weighted average multipliers of aggregate global sector output at the 17-sector aggregation level, specifying the source of emissions as a share of the multiplier: direct emissions of the sector in question, intermediate inputs and consumption of fixed capital, each separated into material and non-material components.

GHG emissions multiplier	Absolute	Direct	Inputs		Capital	
kg CO_2e/EUR			Material	Non-material	Material	Non-material
Agriculture, hunting, forestry & fishing	2,6	66 %	1 %	27 %	3 %	3 %
Mining & quarrying	2,3	68 %	7 %	18 %	5 %	2 %
Food production, beverages & tobacco	1,4	11 %	6 %	74 %	5 %	4 %
Textiles, leather & wearing apparel	1,5	13 %	10 %	64 %	8 %	4 %
Petroleum, chemicals & non-metallic mineral products	2,2	32 %	26 %	34 %	6 %	2 %
Electrical & machinery	1,1	5 %	45 %	34 %	12 %	5 %
Transport equipment	0,9	5 %	45 %	33 %	11 %	5 %
Manufacturing & recycling	1,3	18 %	27 %	42 %	9 %	4 %
Electricity, gas & water	8,4	74 %	1 %	22 %	2 %	1 %
Construction	1,1	4 %	62 %	22 %	9 %	3 %
Sale, maintenance & repair of vehicles; fuel; trade; hotels & restaurants	0,3	13 %	6 %	47 %	20 %	13 %
Transport	1,0	46 %	4 %	36 %	8 %	6 %

Post & telecommunications	0,3	9 %	7 %	31 %	27 %	25 %
Financial intermediation & business activity	0,4	12 %	9 %	36 %	26 %	17 %
Public administration; education; health; recreation; other services	0,5	13 %	11 %	53 %	14 %	9 %