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No mining activities, no environmental impacts? Assessing the carbon footprint of metal requirements induced by the consumption of a country with almost no mines

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Highlights

- The metals sector is responsible for 13% of the total French carbon footprint
- Iron and steel production is the main contributor to this share
- France outsources 79% of the corresponding GHG emissions
- These emissions are mainly outsourced in the European Union and in China

Abstract

All economies rely today on metal use either in the construction or energy sectors or in more advanced technology sectors. Nevertheless, not all countries have mining industries, which implies that these countries need to import primary metal concentrates and semi-finished goods containing metals to fulfill their final consumption. By importing these goods, they also import their associated environmental externalities. Considering the French metropolitan territory where mining industries are on hold since the 1990’s, this study assesses the impacts on climate change of metals-related activities (i.e. mining, production and recycling) induced by the French final demand, as well as their share in the total French carbon footprint. The EXIOBASE v3.3 hybrid database is used to perform the assessment, showing that the metal sector represents 13% of the total French carbon footprint. This contribution is mainly due to the “iron and steel production” activities that are linked to the “construction” and “motor vehicles, trailers and semi-trailers” goods consumed in France. The assessment also shows that France outsources 79% of the metal sector GHG emissions induced by its consumption. 55% of these emissions occur in the European Union and more than 17% specifically in China. Therefore, despite metallic ores are pratically not anymore mined in France, the embodied metal on the French final demand indirectly generates large greenhouse gases emissions abroad (in particular CO2). This detailed overview can be used as support to policy-making, e.g. regarding actions on metal domestic production, trade and more generally supply chains, potentially key to reduce the share of metals in the French carbon footprint. Finally, three major rooms of improvement are identified to refine the assessment of the contribution of the metal sector to the whole environmental footprint of French consumption.

1. Introduction

1.1. Global warming and carbon footprint

The link between greenhouse gases (GHG) anthropogenic emissions and global warming is well established (IPCC, 2018). The Paris climate agreement, signed and approved during the 21st conference of parties, aims at limiting the global warming by 2°C above pre-industrial levels. To prove their determination in reaching this ambitious objective, a large majority of countries published their intended nationally determined contributions (INDC) in which they described, in particular, their targets in terms of GHG emissions mitigation (Rogelj *et al.*, 2016). The scope of these goals is, mainly, national; in other words, only domestic emissions are considered (UNFCCC, 2016). However, in a context of globalization, where for example, OECD countries generated 30% to 50% of foreign emissions as a consequence of their final demand in 2011 (Wiebe and Yamano, 2016), one may raise the question of responsibility regarding GHG emissions. Should the producers or the consumers of goods and services be considered responsible for these emissions and their associated environmental impacts? (Arto, Rueda-Cantuche and Peters, 2014)

The INDC of France follows the one submitted by the European Union (EU) and targets a 40% domestic reduction in terms of GHG emissions by 2030 compared to 1997 (European Commission, 2015). However, in the "energetic transition for green growth" act adopted in August 17th 2015, France defined a low carbon strategy that states, in particular, that the national effort to limit GHG emissions must not have an impact on emissions embodied within the imports (Légifrance, 2015). To assess these emissions, the French government defined a carbon footprint indicator that considers all GHG emissions induced along their supply chains by the products, goods and services consumed in France through the final domestic demand (i.e. the private and public final consumptions and investments - gross fixed capital formation - , the changes in inventories and the direct emissions from households (Kleiber and Vey, 2016)). The French administration uses environmentally-extended input-output analysis (EE-IOA) to implement the calculations of this indicator, considering three GHGs: CO_2, CH_4 and N_2O (for more information on EE-IOA with environmental extensions see Baude, 2018). Domestic production and production-based emissions are drawn from national statistics; emissions associated to French imports are calculated using EE-IOA with data representative of the EU and adjusted for different world regions (Baude, 2018). The European statistics organization, EUROSTAT, also determines the carbon footprint induced by the European consumption by applying another EE-IOA framework based on European data. In this framework, the assumption of "domestic technology" is applied on imports: it assumes that the imported products are produced with similar production technologies to those implemented in the EU (Eurostat, 2018b). To overcome the long-made "domestic technology" assumption, many research projects worked on the extension of the EE-IOA framework to several regions and developed environmentally extended multi-regional input output (EE-MRIO) frameworks. Based on this framework, numerous papers and works have aimed at assessing the carbon footprint such as (Boitier, 2012; Institute for Prospective Technological Studies, 2012; Arto, Rueda-Cantuche and Peters, 2014; Moran and Wood, 2014; Wiebe and Yamano, 2016; Ivanova *et al.*, 2017).

1.2. The contribution of the metal sector to GHG emissions

The world consumption is, today, relatively dependent on metals. These latter are consumed in most sectors from housing to transportation as well as communication or energy production. According to the International Resource Panel (IRP), the quantity of materials (including metals) used in the economy has tripled from 1970 to 2017 (IRP, 2017). The IRP prospects that the extraction of metal ores will increase at a yearly average of 1.7% from 2015 to 2060 if historical trends of consumption continue (IRP, 2019). Similar tendencies have been observed in studies dedicated to some specific metals, such as iron (whose projected demand has been calculated as three to four times higher in 2050 compared to 2010) or copper (Schipper *et al.*, 2018). In particular, one potential cause of this increasing consumption could be the worldwide energetic transition requiring the development of renewable energy technologies (Vidal, Goffe and Arndt, 2013; World Bank Group and EGPS, 2017; Månberger and Stenqvist, 2018). Overall, economic growth leads to an even more important growth in metal footprint (Burke, 2018).

The production of metals is an energy-intensive industrial sector that, accordingly, contributes to the global emissions of GHG. In 2010, the Intergovernmental Panel on Climate Change (IPCC) reported that the metal sector (including ferrous and non-ferrous metals) was responsible for about 20% of the worldwide emissions (Fischedick *et al.*, 2014). These emissions are primarily due to the energy consumption necessary to process the ores into metals. Moreover, the energy consumed by the metal industry (e.g. aluminum and steel) is sometimes coal-based, therefore generating important GHG emissions. By 2050, the GHG emissions driven by the metal demand are prospected to rise by a factor of 1.2 to 1.5 (van der Voet *et al.*, 2019).

Since the beginning of the 1990's, metal extractive industries are on hold in the French metropolitan territory (BRGM, 2007b, 2007a). Therefore, France now has to import all primary metal concentrates needed for its consumption as well as a part of finished and semi-finished products containing metals. Consequently, France also imports the GHG emissions associated to metals extraction and processing activities implemented in other countries.

1.3. Objectives of this study

This context of globalized trade leads to the outsourcing of part of the environmental impacts induced by the domestic consumption. Some studies already focused on the carbon footprint induced by French consumption, with a focus on impacts embodied in products and services consumed (Hertwich and Peters, 2009) and on transportation required to fulfill French consumption (Hawkins and Dente, 2010). Such a kinf of assessment is also performed and updated regularly at the French scale by the French administration (Pasquier, 2012). This paper contributes to better understand the origin of GHG emissions drivers, where originis are coming from French consumption. More specifically, the assessment of those drivers us made by focusing on the metal sector and on the climate change impacts of metal production induced by French final demand. The goal of this assessment is to provide informative inputs to policy makers to help them to enhance the design of climate change mitigation policies. In order to give an overall overview of these impacts, the study aims at answering the following questions using MRIO approaches, as a support to the definition and prioritization of actions to reduce GHG emissions.

- What is the contribution of the metals sector to the French carbon footprint, i.e. to the global emissions induced by the French final demand?
- What activities, relative to metals, are the greatest contributors to this footprint (considering extraction, production and recycling activities)?
- Which metal has the greatest contribution to the French carbon footprint?
- Which categories of products and services carry the burden associated with metal production?
- In which countries does the French consumption induce GHG emissions from metal production activities?

2. Materials and methods

2.1. Choice of the EE-MRIO databases relevant for the study

2.1.1. Overall considerations on EE-MRIO databases

MRIO databases are developed to take into account industries interdependencies within the regional economy but also within the inter-regional economy. In this respect, for a given year, a MRIO database contains a table describing the intermediary consumption of each economic activity taking into account inter-sectorial and inter-regional economic exchanges expressed either in monetary or hybrid (that is, including both monetary and physical) units, as well as tables representing the domestic final demand. Finally, an EE-MRIO database also contains a table of direct emissions and extraction broken down per economic activities as well as a table representing the direct emissions and extractions of resources associated with the final demand (e.g. CO_2 emissions generated by the consumption of fossil fuels by households for heating and transportation).

The existing MRIO databases were developed at different geographical scales: regional scale such as for China (Mi *et al.*, 2017), or Brazil (Munoz Castillo *et al.*, 2019); continental level, e.g. Europe (through EUROSTAT and the FIGARO project (Eurostat, 2018a)); worldwide level e.g. WIOD (Timmer *et al.*, 2015), EORA (Lenzen *et al.*, 2012, 2013), GTAP (Hertel, 1997; Aguiar *et al.*, 2019), EXIOBASE (Tukker *et al.*, 2013; Wood *et al.*, 2014; Stadler *et al.*, 2018) or TiVA (OECD, 2019). These worldwide MRIO databases are also EE-MRIO (except for TiVA) that are continuously updated and upgraded (for example the third version of EXIOBASE was released in 2018 and the tenth version of GTAP in summer 2019). Nevertheless, these databases differ in some aspects such as the temporal, geographic or technological coverages. Moreover, the main data sources and the main assumptions considered for building the tables are also specific to each database. Table 1 gives a summary overview of these differences for five MRIO databases, a more complete assessment is available in the supplementary information. Many authors had an interest in databases comparison; see for example Arto *et al.* (2014), Moran and Wood (2014), or Owen (2015) who provide an overview of the effects these differences have on results.

2.1.2. Representation of metals in MRIO databases

As each EE-MRIO database differs in its technological coverage, the level of aggregation of economic activity branches also differs depending on the database. Given the goal of this paper, a special attention is here paid to the aggregation of the activities related to the metal branch (from mining to production and recycling). When looking at industrial classifications used in EE-MRIO such as ISIC (International Standard Industrial Classification of All Economic Activities) or NACE (Statistical Classification of Economic Activities in the European Community), metals activities are included in both “mining and quarrying” and “manufacturing” categories when considering the first level of aggregation. At the second level, considered in some EE-MRIO databases as shown in Table 1, metal activities are included in both “mining and quarrying” and “basic metal manufacturing” activities. The first one encompasses the activities related to the extraction of non-energetic mineral resources (e.g. metallic, non-metallic ores etc.) as well as energetic fossil resources (e.g. coal, natural gas etc.), and also the activities that process raw materials prior to their selling (crushing, grinding, washing, drying, sorting, ore beneficiation, natural gas liquefaction or solid fuels conglomeration). At this level of aggregation, metals cannot be clearly identified. Conversely, the “basic metals manufacturing” activity exclusively focuses on metallurgical activities taking into account all physico-chemical transformations applied to produce new products (including recycling) e.g. smelting and refining of ferrous and non-ferrous metals, alloys and super alloys production and rolling, drawing and extruding activities. Therefore, at this level of aggregation, production specificities related to each metal cannot be assessed. Given its goal of “Developing an optimal set of indicators to monitor European progress towards resource efficiency” (Eisenmenger *et al.*, 2014), EXIOBASE v3 proposes a disaggregation of the “mining and quarrying” and of the “manufacturing of basic metals” activities so as to distinguish seven categories of metals as well as recycling activities (see Table 1). EXIOBASE v3.3.11 (in the following referred to as EXIOBASE V3) is therefore chosen for this study, in particular considering the hybrid version (industry by industry) for the year 2011 (Merciai and Schmidt, 2018).

Table 1: Comparison assessment between five EE-MRIO databases - A summary

	GENERAL INFORMATION				
	WIOD	**EORA**	**GTAP10**	**EXIOBASE V3.3.11**	**TiVA**
Database first funders	EU - FP7	Australian research council	Purdue University	EU - FP7	OCDE
Creation date (project timeline)	2009-2012	2009-2011	Continuous development since 1990	2012-2016	Continuous development
Pionneering paper	Timmer *et al*, 2015	Lenzen et al., 2012, 2013	Aguiar *et al.*, 2019	Merciai and Schmidt, 2016	OECD, 2018b
	ENVIRONMENTAL EXTENSIONS				
	WIOD	**EORA**	**GTAP10**	**EXIOBASE V3.3.11**	**TiVA**
Carbon footprint	Yes	Yes	Yes	Yes	Yes - based on International Energy Agency (IEA) data
Considered GHG	CO_2, CH_4, N_2O	CO_2 emissions linked to different activities GHG emissions expressed in CO_2 eq (25 GHG taken into account)	CO_2, CH_4, N_2O and fluorinated gases	CO_2, CH_4, N_2O and fluorinated gases	*TiVA had no environmental extensions table, but ~~the~~ it can be coupled with data from IEA considering CO2 emissions*
Data sources for modelling	National statistics EDGAR database IEA IPCC	IEA OECD UN EDGAR database National statistics	EDGAR database FAOSTAT	IEA TNO model on emissions (TEAM) IPCC	IEA
	GEOGRAPHICAL AND TEMPORAL COVERAGE				
	WIOD	**EORA**	**GTAP10**	**EXIOBASE V3.3.11**	**TiVA**
Number of modelled regions	40 (43 in the 2016 updated version) + 1 Rest of the World region (ROW)	187	121 including 20 ROW~~s~~	43 + 5 ROW	60 + one region EU27
Available years	1995-2009 (2000-2014 in the 2016 updated version)	1990-2015	2004, 2007, 2011, 2014	2011	1995-2014

	ECONOMICAL COVERAGE				
	WIOD	**EORA**	**GTAP10**	**EXIOBASE V3.3.11**	**TiVA**
Number of economic activities modelled	35 (56 in the 2016 updated version)	15909 (individual sectors, by countries for the full version). 26 in the version EORA26	65	163	48
Economic activities related to the metal sector	- Mining and quarrying - Basic metals and metal products	In the full version, the disaggregation depends on the country considered. In EORA26, two activities are considered: - Mining and quarrying - Metal products	- Other extractions - Ferrous metals - Metals nec	- 3 activities (mining, production and re-processing) for the following metals: iron, copper, aluminum, precious metals, lead/zinc/tin, other non-ferrous - Mining of nickel ores and concentrates	- Mining and quarrying - Basic metals

2.2. EE-MRIO databases manipulation

EXIOBASE V3 contains the information described in section 2.1.2. These tables are the inputs to the Leontiev's equations (Leontief, 1970) applied to IO frameworks standing that the total output is the sum between intermediate consumptions and final demands. As mentioned by severeal authors, this equality is also valid for MRIO framework (see for example Peters, 2008; Cadarso, Monsalve and Arce, 201*8; Beylot et al*, 2019) leading to Equation 1:

$$x = A.x + y$$ **Equation 1**

Where x is the total output required to satisfy the final demand y : the "sum of the final consumption, investment and stock building expenditures by the private and general government sectors" (OECD, 2018a)*;*

A is the matrix of technical coefficients obtained by dividing the intermediate consumption (*MRIO*) by the total output ($A_{.,i} = MRIO_{.,i} / x_i$ for i in [1; n*m] where n is the number of sectors represented in the database – 163 in EXIOBASE v3 – and m the numer of regions represented in the database – 48 in EXIOBASE v3).

When looking specifically at French final demand y_{FR}, Equation 1 can be rewritten as:

$$x_{W,FR} = A.\, x_{W,FR} + y_{FR}$$ **Equation 2**

Where $x_{W,FR}$ is the world total output required to satisfy y_{FR}. To calculate the global emissions induced by the French final demand, Equation 2 can be derived to:

$$x_{W,FR} = (I-A)^{-1}.y_{FR}$$ **Equation 3**

And to

$$g_{FR} = B.\, (I-A)^{-1}.y_{FR} + e_{FR} = B.\, x_{W,FR} + e_{FR}$$ **Equation 4**

Where g_{FR} is the vector of total GHG emissions induced by the French final demand y_{FR};

e_{FR} is the vector of French direct GHG emissions, directly generated by the French final demand;

B is the matrix of environmental interventions (E) expressed by unit of production ($B_{.,i} = E_{.,i} / x_i$ for i in[1; n*m]).

To answer the questions listed in section 1.3, Equation 4 can be modified to express the emissions either by sectors (Equation 5) or by products and services of the final demand (Equation 6).

$$g_{FR} = B.< x_{W,FR} > + e_{FR}$$ **Equation 5**

<.> stands for the algebraical operator transforming a vector into a diagonal matrix

$$g_{FR} = B.\, (I-A)^{-1}.<y_{FR}> + e_{FR}$$ **Equation 6**

In other words, Equation 5 expresses the GHG emissions of each sector regardless of their position within the value chains of products and services of the by French final demand; Equation 6 expresses the total emissions (direct and indirect) of each category of products consumed by the French final demand and so allocated to the "consumer" in opposition to Equation 5 in which they are associated to the "producer" (see Peters, 2008).

Moreover, to specifically assess the categories of products and services that carry the burdens associated with metal production, in Equation 6, all elements of B, except the ones associated to the metal sector (as listed in Table 1), are set to 0. Finally, to express the emissions of g_{FR} into a carbon footprint, characterization factors are applied to the three GHGs. The employed characterization factors are drawn from the ILCD 2011 Midpoint method (European Commision - Joint Research Center - Institute for Environment and Sustainability, 2011). All the matrix calculations are performed using R software (R Core Team, 2018).

3. Results and discussion

3.1. The metal sector within the French carbon footprint

By applying Equation 4, the total French carbon footprint in 2011 amounts to 639 Mtonnes of CO_{2eq}. In this calculated carbon footprint, 127 Mtonnes (about 20%) are induced by direct emissions of the French final demand (such as emissions from transport and heating) that are represented by the term e_{FR} in Equations 4 to 6. Other main contributors to this footprint are consumption from households (about 45%) and gross fixed capital formation (about 20%). This footprint is mainly induced by the CO_2 emissions (about 76%), followed by CH_4 emissions, both fossil and biogenic (about 19%) and N_2O emissions (about 5%).

In order to assess the contribution of economic activities to the French carbon footprint, Equation 5 is applied. For a better representation of the results, it is chosen to aggregate the 163 sectors of EXIOBASE into 36 economic activities (using the "intermediate ISIC aggregation" categories). Figure 1 shows the contribution of the aggregated economic activities to the French carbon footprint, as well as the contributions per type of GHG[1]. The contribution of the activity "Basic metals and fabricated metals" is mainly due to CO_2 emissions. As for the "Mining and quarrying" sector, the main contributor is $CH_{4\ fossil}$ primarily induced by the "extraction of crude petroleum and services related to crude oil extraction" and from the activity "Mining of coal and lignite" (about 23%). In the extraction of crude petroleum, CH_4 emissions are, in particular, due to operations such as gas venting that lead to direct releases (see Masnadi *et al.*, 2018 for a review). In the coal mining sector, these emissions can be explained by the CH_4 stored within coal that is subsequently released during mining operations (Climate Technology Centre and Network, 2010). Finally, the $CH_{4fossil}$ emissions occurring in the "Manufacturing and Recycling" sector are mainly due to the fugitive emissions induced by waste landfilling.

Figure 1 also shows that the activity "Basic metals and fabricated metals" is the third most contributing activity in terms of GHG emissions along with the activities "Electricity, Gas and Water Supply" and "Agriculture, Hunting, Forestry and Fishing". The "Basic metals and fabricated metals" sector contributes to 13% of the GHG emissions induced by the French consumption, including all production and retreatment processes of the metals sector. It is, for instance, three times higher than the contribution of "Air transport". The contribution of metals mining is aggregated within the "Mining and quarrying" sector (8% of the total GHG emissions) in which the contribution of metallic ores mining only represents 2%, thus showing that most GHG emissions attributed to the metal sector are rather generated during the production stages.

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[1] Results for the 163 economic activities in EXIOBASE v3 and the concordance table can be found in the supplementary information

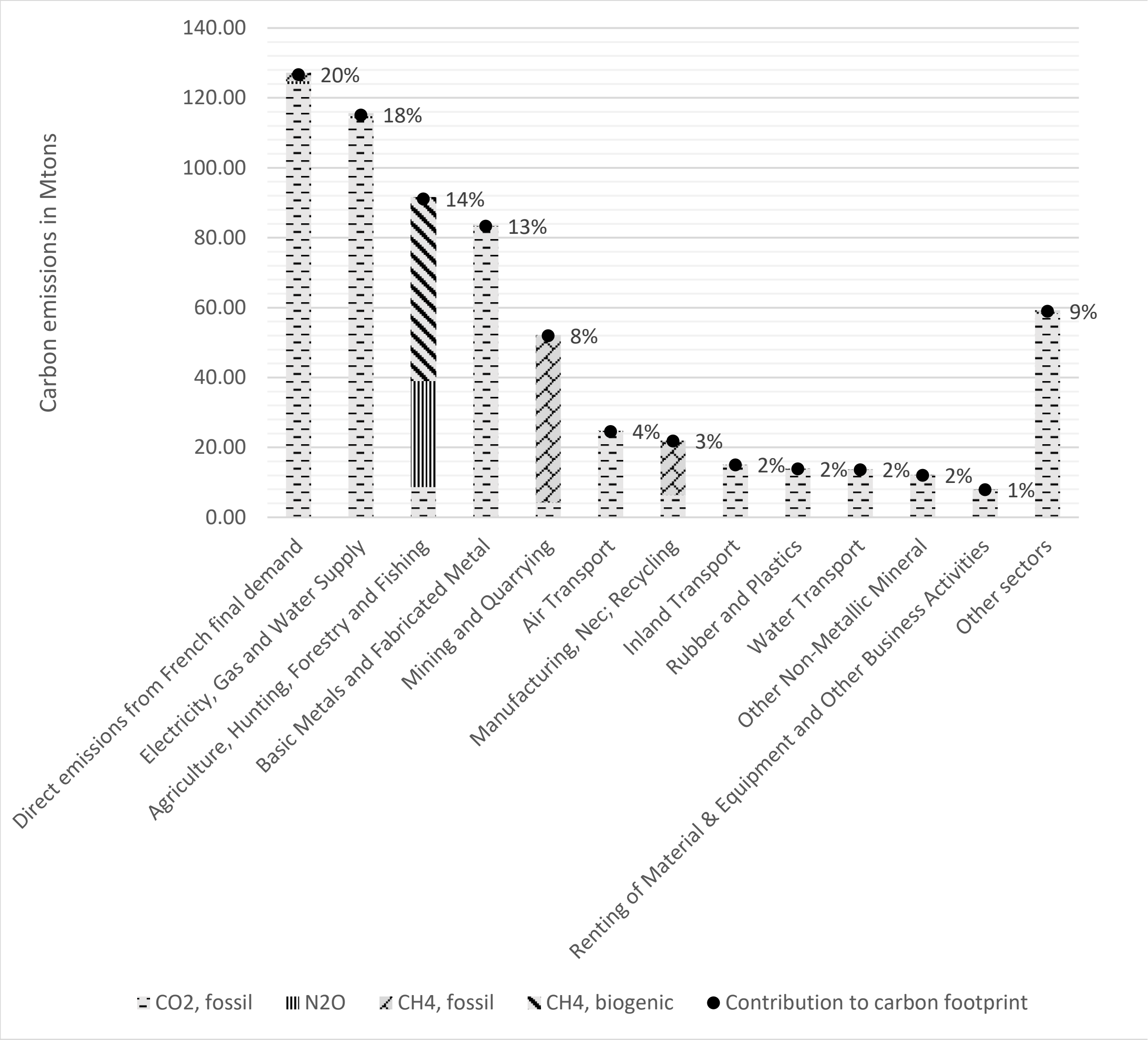

Figure 1 : Contribution by economic activities and by type of GHG to the French carbon footprint in 2011.

3.2. Contribution analysis per metals and activities

When solely focusing on emissions resulting from the metals sector induced by the French final demand, the contribution of the different metal activities can be broken down as:

- 1.6% for the metallic ore mining;
- 98.4% for the metals and alloys production;
- 0.01% for the metal re-treatment.

Processing of concentrates into metals and alloys are by far the activities that contribute the most to the “metal carbon footprint”. This slightly differs when assessing these contributions by type of metals (see Figure 2). Regarding iron and steel, the production stages outweigh by far the other activities in terms of carbon emissions. Similarly, production activities are also the main contributors to carbon emissions related to copper, other non-ferrous metals and aluminum. Concerning precious metals and the category lead/zinc/tin, the mining and production activities have similar orders of magnitude in terms of emissions. On the other hand, re-treatment activities (i.e. recycling) only contribute in a relatively low extent to carbon emissions of each metal, in comparison with mining and production activities. Concerning the aluminum production specifically, a high demand of electricity is needed, as the IEA reports 14.7MWh/tonne of aluminum produced in a global perspective (IEA, 2019). This electricity is either internalized in the aluminum production activity or supplied from the network. Following the MRIO approach applied here, electricity consumption whose emissions are not internalized within the aluminum activity are not considered in the results. In other words, part of the contribution of the "Electricity, Gas and Water Supply" sector to the total French carbon footprint (in Figure 1) is induced by the "Basic Metals and Fabricated Metals" and the "Mining and Quarrying sectors".

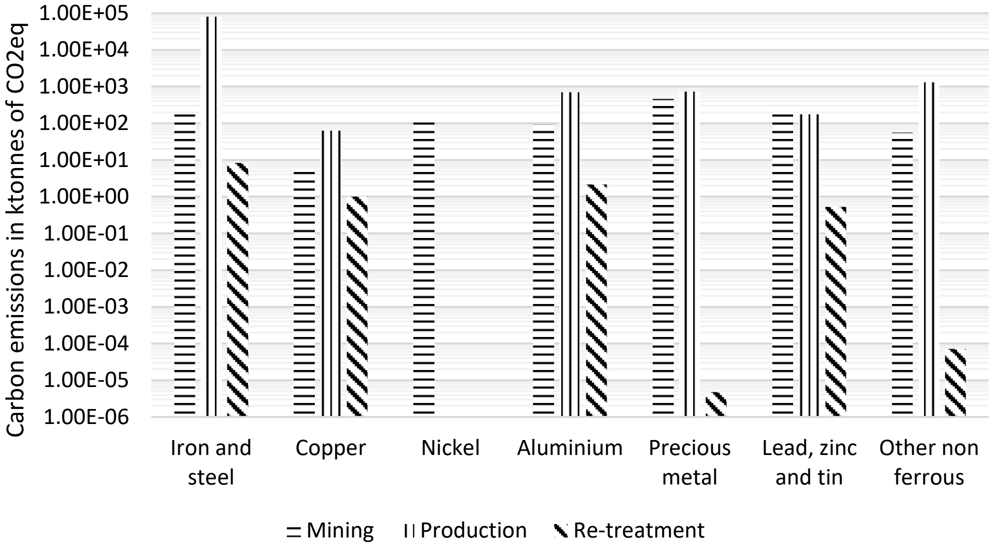

Figure 2 : GHG emissions induced by the activities related to the metals sector and needed to fulfill the French final demand, for the different metals considered in EXIOBASE v3 – expressed in logarithmic scale

Figure 2 shows the family of metals and alloys that contribute the most to GHGs emissions induced by the French final demand. Production of iron and steel contribute to about 95% of GHGs emissions of the metal sector and to about 12% of the French carbon footprint. Iron and steel production is followed by other non-ferrous metals (1.6%), precious metals (1.4%) and aluminum (1.0%) production. The contribution of these activities is either driven by their contribution to the total output vector (x_{FR}) shown in Table 2 or by their carbon intensity (i.e. the amount of GHGs emitted by tonne of production stored in the B matrix; Figure 3). Iron and steel activities contribute to about 90% of the metal sector activities of $x_{W,FR}$ (that is, 90% of the French metal footprint is made of iron and steel). This explains the high contribution to the French carbon footprint, while the carbon intensity of the iron and steel activities (especially production) has the same order of magnitude than that of aluminum and other non-ferrous metals productions. Figure 3 shows in particular a difference of almost three orders of magnitude between the carbon intensity of precious metals production and the other metals production, in line with observations from other studies focusing on the environmental impacts of metal production (e.g. Nuss and Eckelman (2014)). However, the mass of precious metals induced by the French final demand is five orders of magnitude lower than that of iron and steel, explaining their very limited contribution to the French carbon footprint.

Table 2 : Amount of the activities related to the metal sector in the total output vector $x_{W,FR}$ – expressed in ktonnes

	Mining	Production	Re-treatment

Iron and steel	34087.0	49159.9	270.7
Copper	199.6	190.3	0.6
Nickel	25.6	NA	NA
Aluminium	1386.5	951.8	8.4
Precious metals	0.2	0.2	0.00004
Lead, zinc and tin	861.2	787.2	7.9
Other non ferrous	925.2	1219.3	0.1

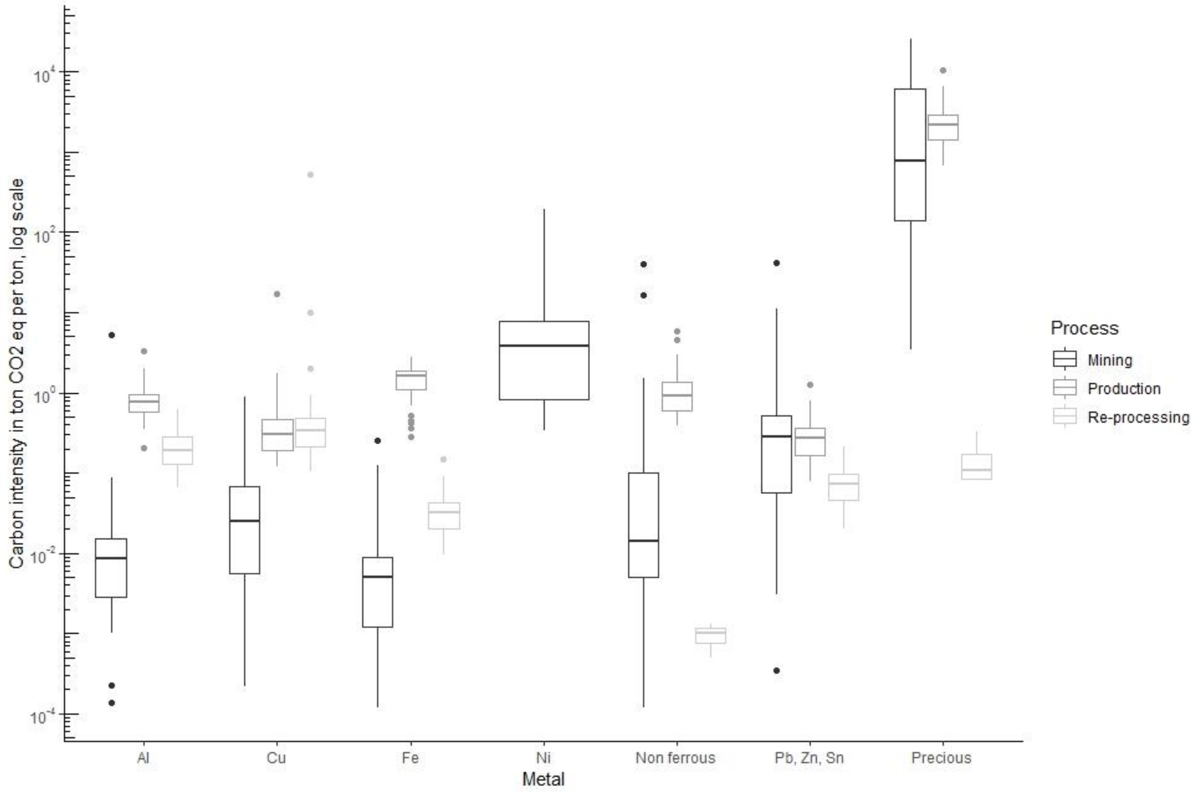

Figure 3 : Carbon intensity distributed among countries for each activity of the metal sector, log scale. Fe – activities related to the iron and steel sector, Non ferrous – activities related to the other non ferrous sector, Precious – activities related to the precious metal sector

3.3. Contribution analysis per country

EE-MRIO assessment also enables identifying the countries where GHGs induced by the French final demand are emitted. For the different families of metals, results are presented in Table 3. Emissions occurring domestically in France are mainly due to the iron and steel as well as aluminum production. Production and re-treatment activities generating GHGs emissions are mainly located in France and China, while emissions due to extraction activities mainly occur in Africa, China and Asia. As iron and steel production has the highest contribution (among the metal sector) to the French carbon footprint, France, China and Germany are globally the three countries with the highest share of emissions induced by the metal sector. This share respectively amounts to 21.0%, 17.4% and 12.2% for France, China and Germany. When looking at emissions occurring in the EU, the latter represents 55% of the GHG emissions from the metal sectors induced by the French consumption while 45% of these emissions occur outside of the EU. In total, France outsources 79% of the emissions related to the metal sectors and induced by its consumption.

Table 3 : Break down by countries and by type of metals of the metal sectors GHG emissions induced by the French final demand (RoW: Rest of the World region)

Metals and alloys	Country	Countries contribution to the emissions related to each metal	Contribution of metals and alloys to the total French carbon footprint
Iron and steel	France	21.6 %	12.6%
	China	17.8 %	
	Germany	12.8 %	
	Others	47.8%	
Copper	China	12.1 %	0.01%
	RoW : Asia and Pacific	9.0 %	
	Row : Latin America	8.2 %	
	Others	70.7%	
Nickel (only considering mining)	South Africa	43.1 %	0.02%
	RoW : Asia and Pacific	30.6 %	
	RoW: Africa	10.6 %	
	Others	15.7%	
Aluminum	France	22.4 %	0.13%
	China	15.0 %	
	RoW : Middle East	11.3 %	
	Others	51.3%	
Precious metals	RoW : Africa	35.4 %	0.19%
	RoW : Latin America	23.5 %	
	Poland	9.1 %	
	Others	32.0%	
Lead, zinc, tin	RoW : Africa	24.1 %	0.06%
	France	13.1 %	
	Indonesia	10.3 %	
	Others	52.5%	
Other non ferrous	RoW : Africa	21.9 %	0.22%
	RoW : Asia and Pacific	21.5 %	
	South Africa	13.0 %	
	Others	43.6%	

3.4. Metal carbon content of elements of the French final demand

To assess which category of products and services carry the burden associated with the “metal carbon footprint”, Equation 6 is applied by modifying the *B* matrix so as to only consider emissions resulting from the metal sector (see section 2.2). Elements of the French final demand with the highest metallic carbon content are displayed in Figure 4 using the full EXIOBASE v3 nomenclature. “Construction” “Manufacture or motor vehicles, trailers and semi-trailers” products have the highest metallic carbon content (that is, the GHG emissions associated with metal production along the supply chain of these consumed products and services). These two sectors have both a relatively medium contribution to the French final consumption but their direct requirements in terms of “fabricated metals products” and “basic iron, steel and ferroalloys products” are important, explaining their high contributions to the metallic carbon content. For example, the French “Manufacture of motor vehicles, trailers and semi-trailers” activity directly requires 45 tons of “fabricated metals products” and “basic iron, steel and ferroalloys products” per million euro of vehicles produced. “Construction” and “Manufacture or motor vehicles, trailers and semi-trailers” products also carry the largest share of the burden associated with the total French carbon footprint.

In the list displayed in Figure 4, mainly products with metals as main constituents are found, in addition to two service activities “Public administration and defense, compulsory social service” and “Health and social work” which require metals along their supply chains (for infrastructure for example). This contribution can be explained by their important contribution to the French final consumption and especially to the final consumption by government while final consumption by households is primarly driven by “Real estate” and “Hotels and restaurants” activities.

About 38% of the metallic carbon content is embodied in imported manufactured products, especially from the following sectors: “Manufacture of machinery of equipment”, “Manufacture of electrical machinery and apparatus” and “Manufacture of radio, television and communication equipment and apparatus”. These imported products are mainly coming from France major trade partners such as the EU and China.

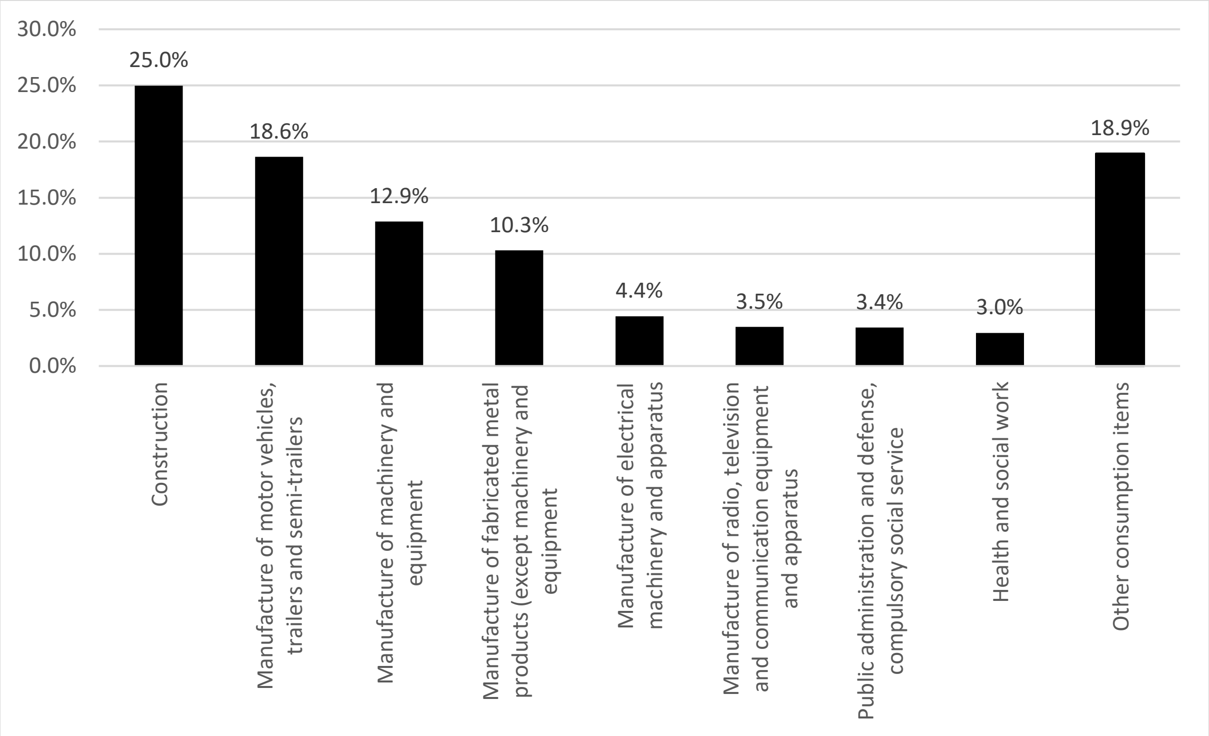

Figure 4 : Repartition of the metallic carbon content of activities consumed by the French final demand

3.5. Results comparison with WIOD database

A similar assessment was made using the WIOD database and its temporal series (from 1995 to 2009). Given that the WIOD database is more aggregated than EXIOBASE v3 in terms of sectors (see section 2.1.2), the same level of interpretation cannot be reached here. Nevertheless, this assessment gives results that can be compared to those obtained with EXIOBASE v3. In a first place, the metal sector in WIOD only considers the "Basic metals and metal products" activity. So, neither the mining nor the retreatment activity are considered here. The contribution of the metals sector to the global French carbon footprint varies from 5.4% to 6.6% between 1995 and 2009 with the highest peak reached in 2007. If the contribution is slighter than the one calculated in EXIOBASE v3 (13% as shown in Figure 1); it shows a relative stability through the years. These differences can be explained by various factors such as data sources for emissions and trade or models used in both databases.

When looking at the country contribution to these GHG emissions from the metals sector induced by the French final demand, similar conclusions to those observed with EXIOBASE v3 can be drawn. The assessment with the WIOD database shows that between 1995 and 2009, emissions occurring in France dropped from about 30% to 20% when considering metal production only, while emissions occurring in China increased from 6% to 16%. In the meantime, the overall contribution of the metal sector remained relatively stable in the French carbon footprint. This rise of emissions occurring in China can be explained by the increase of their share in the global iron and steel market from 15% to about 45% between 1995 and 2009 (International Iron and Steel Institute, 2000, 2010).

4. Conclusions and perspectives

The main findings of this study that aimed at assessing the contribution of the metals sector to the French carbon footprint in 2011 are the following:

- The metal sector (including mining, metal production and retreatment activities) contributes to 13% of the French carbon footprint; primarily due to the activity "Iron, steel and ferro alloys production";
- Activities related to metals and alloys production have a much larger contribution to the French carbon footprint than mining and re-treatment;
- GHGs emissions of the metals sector induced by the French final demand mainly occur in France, China and Germany. Overall, 79% of these emissions occur out of the French territory, despite being associated to the French consumption;
- Products that carry the burden associated to metal production are products that are mainly made of metals, and most of all of steel and iron.

Such results can lead to actions for reducing the carbon footprint of a nation induced by a specific sector. Here for example the economical activity "Production of iron, steel and ferro alloys" has the greatest contribution. Reducing the amount of products containing steel in the final demand (provided that substitution products do not have a larger carbon footprint that steel containing products), GHG-saving technological improvements in production processes or increasing the fraction of recycled steel in the products needed to fulfill French final demand are three options that may help reduce the carbon footprint linked to the metal sector. Furthermore, such results also show that such solutions should be globalized, as emissions are not only occurring on the national territory. French carbon footprint is also dependent on national climate policies that are implemented in other countries. For example, if China follows its INDC that aims at reducing by 2030 its CO_2 emissions per capita by 60 to 65% comparing to 2005, it will have a direct incidence on the French carbon footprint. EE-MRIO approaches can accordingly help national and international policies to answer environmental challenges linked to consumption and globalization of trade. This assessment focused on French final demand but, similar conclusions could be drawn with respect to other countries such as Germany, Luxembourg or Switzerland with also almost no mining activities on their territory, some metals production activity (especially steel mills) and an economy strongly driven by the service sector. Moreover, when considering resources productivity indicators assessing a country's materials consumption and materials footprint, countries such as Japan or South Korea have also a profile similar to France with economies that heavily rely on metal ores imports (UNEP International Resource Panel, 2016), and one may imagine similar trends and results to the French case.

However, in this study, only the carbon footprint is considered therefore not taking into considerations the whole range of environmental impacts associated with the production and consumption of metals. When considering other impacts such as ecotoxicity, human toxicity or mineral resource use, the contribution of metals to French environmental footprints might be greater than the ones obtained for carbon footprint. For example, Beylot *et al.* (2019) show that, for the European final consumption, metal containing products carry the highest burdens related to ecotoxicity, toxicity and mineral resource use and Ottelin *et al.* and Wiedmann *et al.* show that the construction sector contributes also highly to material footprint (i.e. to the total mineral resource use) of nations (Wiedman*n et al*, 2015; Ottelin, Heinonen and Junnila, 2018).

EE-MRIO databases contain aggregate information related to metals that may lead to uncertainties while interpretating results:

1. If the base metal sectors are well represented in databases such as EXIOBASE, there are, for example fewer information regarding technological metals (strategic metals necessary for the digital and energy transitions – lithium, rare earths, gallium for example). When available, the lattery are aggregated within the “precious metals” or the “other non ferrous metals” sectors. Even if the volume of production and subsequently of consumption of these technological metals is relatively low, the question of their contribution to the carbon footprint of a nation is not without interest as they expect to play a major role in the energy transition policies needed to decarbonize our societies.
2. If countries from the EU or some from the OECD are well represented, it is not the case for some main actors of the metal markets. Regarding copper for example, Chile and Peru respectively represented 27.5% and 11.6% of worldwide copper ore extraction in 2016. Moreover, in the same year, Chile was producing 11.2% of worldwide refined copper (BRGM, 2018). Both of these countries are aggregated in the region Rest of the World – America in EXIOBASE and so cannot be distinguished with this database.

Disaggregating metal specific sectors and Rest of the World regions might improve the evaluation of metals stocks, flows and associated environmental impacts using EE-MRIO databases. Dissaggregation is however a data intensive task that relies on the quality of data inputs. Substance flows analysis (SFA), that quantifies flows and stocks of a substance in a given economy, can be for example a source of data to disaggregate EE-MRIO databases alongside specific databases on product compositions and stocks (such as life cycle inventory databases or stand-alone databases). Besides gathering data, MRIO disaggregation imples balancing procedures that ensure for example that the total output of each sector equals the sector’s inputs (see Geschke *et al.*, for a review (2019)). Implementing these balancing procedures and reconciliation algorithms also implies assumptions and uncertainties.

Improving the evaluation of metals using EE-MRIO databases is also linked to a better modelling of environmental extensions associated to the metal sectors, not only affecting the robustness of the carbon footprint as analysed in this study but also of footprints and impacts beyond carbon (e.g. toxicity or mineral resource use). For example, in EXIOBASE, air emissions are quantified using models rather than measured emissions (Stadler *et al.*, 2018) while a very limited number of emissions of metals to water and soil are accounted for (e.g. metals emissions to groundwater resulting from tailings management on mine site are not taken into account in EXIOBASE). Again, refining environmental extensions is a data intensive task that relies on the quality of the data inputs. Gathering and transforming reliable data to enhance EE-MRIO databases can be achieved by close collaboration between database creators and the different stakeholders of metals value chains.

However, such MRIO assessments allow having a clear understanding of the direct impacts a sector has on carbon footprint (or other environmental or socio-economical footprints) induced by a specific final demand. By using time series (EXIOBASE v3 contains time series from 1995 to 2011), evolutions of the results can also be assessed having in mind the limits related to the last year available in MRIO databases. Nevertheless, such assessment do not consider the whole supply chain of these specific sectors. Methods recently developed to consider the supply chains of economic activities (for example to consider the electrical production needed for the “Aluminum production” activity), as proposed for example by Cabernard, Pfister and Hellweg (2019) and (Dente *et al.*, 2019) appear particularly promising in view of further refining the assessment made in this study.

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