Metal footprint and greenhouse gas emissions embodied in South-South trade: a study about the Brazil and China bilateral trade (2000-2019)

Abstract

This paper analyses the greenhouse gas emissions and metal footprint in renewable power value chains associated with international trade between Brazil, China, and the Rest of the World from 2000 to 2019. Using EXIOBASE data, results show a "North-South" trade pattern: Brazil's exports to China are emissions-intensive in agriculture and food production, while China's exports to Brazil are in manufacturing and capital goods. In the Net Carbon Exports indicator, Brazil had a carbon emissions surplus in transactions with China. This result is related to the volume of exports and the emission intensity of Brazil's export structure, as well as China's tendency to increase emissions through consumption due to industrial upgrading in global chains. The results indicate that Brazil's role in renewable energy value chains is in the mining stages, in the bulk and rare metal ore categories. The expressive participation of the extractive sectors in Brazil's exports indicates potential challenges to reducing the metal footprint, due the nature of the heavy industries process. We highlight the principle of shared responsibility as a reference for designing trade policies between developing as this principle considered all the indirect effects on international trade, as well as encouraging a positive and mutual relationship between the countries.

Keywords: Input-output analysis; International trade; Carbon dioxide emissions.
JEL code: F18; Q51; Q54

1. Introduction

The effects of climate change on production and international trade have become a constant concern for policymakers. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), the substantial impacts estimates of climate change on the global economy are the occurrence of the water drawdown, which difficult the food production; the cities and transportation infrastructure, mainly on the cost area, that difficult the economic activity dynamism; and the impact on the health and well-being.

In the last decade, the implementation of policies to mitigate greenhouse gas (GHG) emissions - that is, the greater responsible for the increase in the global average temperature (IPCC, 2018) - has increased, corresponding to the productive decarbonization and energy transition. The Paris Agreement (UN, 2015) has formally attached this compromise through the coalition regime of National Developing Countries (NDC), which aims to reduce emissions and promote more transparency of climate actions. The positive results are observed through the creation of regulatory and economic instruments to increase energy efficiency, the reduction of deforestation levels, and the rapid development of technologies for emissions reduction (IPCC, 2023).

However, in a primer moment, the solutions of the GHG emissions mitigation were oriented to the territorial emissions, it means the emissions generated by the production within the borders of each country. However, the globalization of production and trade has shed light on the emissions transfer through international trade, which considers the emissions based on consumption. That is because, considering the trade dynamics, even if a country gets the goal of reducing the emissions intensity in its production structure, this country's import pattern could potentially generate emissions on trading partners and, in net terms, this has a null effect on total emissions (Grubb et al., 2022).

n addition, related to the discussion of GHG emissions mitigation, countries have implemented strategies to build a low-carbon economy, accelerating the process of energy transition to renewable energy systems. However, as renewable energy is mineral intensive, the process has highlighted the environmental impacts associated with the increase in material demand (Hund et al., 2020). As each country plays a different role in renewable energy value chains, the growth of renewable power plants has been a new driver of environmentally unequal exchange (Fu er al., 2023). The environmental extended multiregional input-output (EE MRIO) analysis has been used as an important tool for understanding pollution transfer through trade flows (Steinberger et al., 2012; Grubb et al., 2022) and for the attribution of emissions responsibility (Lenzen, Murray, 2010; Zhang et al., 2020).

Therefore, this paper proposes to use this tool to investigate the pattern of greenhouse gas (GHG) emissions and material footprint (MF) associated with the bilateral trade pattern between Brazil, China and the Rest of the World (ROW) in the period 2000-2019. The selection of countries is motivated by the trade representativeness of two larger developing economies, defined as a strategic partnership (Oliveira, 2016). Since 2004, China's dynamism has impacted Brazil's export structure, leading to a significant increase in demand for commodities - mainly mining, livestock, and cereals. On the one hand, the demand increased for commodities contributed to the trade surplus, with an average export growth rate of 15% since 2010. On the other hand, this movement favored an increase in the market share of commodity goods in exports, leading to an effect known as the "re-commoditization" of Brazil's export structure (Bertola, Ocampo, 2012).

From an environmental perspective, the rise of Brazilian agriculture sectors has been linked with increased deforestation. In addition, "re-commoditization" promotes low levels of investment in industrial sectors, which means a decline in productivity and energy efficiency. Therefore, Brazil has the challenge of promoting an industrialization model that is compatible with sustainable development while, at the same time, controlling deforestation.

The paper proposes an input-output analysis based on the third version of the EXIOBASE database, which provides data on 163 industries for 44 countries and an aggregate region as the Rest of the World (RoW). The database contains satellite accounts that allow the biophysical data to be obtained. For GHG emissions, we consider emissions of carbon dioxide, methane and nitrous oxide in carbon dioxide equivalent (CO2e) units. For the material footprint, we consider metal ores in four categories: bulk metal ores (bauxite, copper, iron, lead and zinc ores), precious metal ores (silver and platinum group metal ores), scarce metal ores (nickel and tin ores) and other non-ferrous metal ores, expressed in kilotons.

The main contribution is to identify the pattern of GHG emissions and material footprints associated with Brazil's international trade position. In addition, we calculate the Net Exports Carbon Index for the bilateral trade relationship between Brazil and China to measure the aggregate trade surplus in terms of GHG emissions, helping to address responsibility for emissions and align trade policies with production and consumption patterns.

Therefore, beyond this introduction, this paper has four other sections. The second section presents a brief literature review and contextualization of the international insertions and emission patterns of countries' analyses. The third section presents the methodology and database used and discusses the results obtained. Finally, we end the paper with the final considerations.

2. Literature review

2.1 Climate crisis and development

The Sixth Assessment Report (AR6) (IPCC, 2023) pointed out the necessity to take urgent measures to stop the climate crisis. The studies reported the continuous increase of GHG emissions and, consequently, the increase of the global average temperature, caused by the energy sector from non-renewable fossil fuels, changes in land use, lifestyles, and consumption and production patterns of the population.

In this context, the Paris Agreement (UN, 2015) represents a compromise between countries to fight the climate crisis, mainly through the goals of the NDC to reduce GHG emissions. The key goals include: (a) implementing measures to limit the rise in global temperature, ideally keeping it below 1.5ºC compared to pre-industrial levels; (b) promoting skills in climate adaptation projects; (c) advancing technologies and infrastructure to mitigate climate impacts; (d) establishing and applying international financial mechanisms; and (e) strategically planning for resilient economic development (UN, 2015).

According to IPCC (2023), the international community has noticed the commitment to emission mitigation policies, mainly by the incentive on energy transition to renewable sources, such as wind and solar power, the electrification of urban systems, investments in sustainable infrastructure, energy efficiency, demand management, forest and agricultural management, reduction of food waste, etc. The set of mitigation policies promotes cost reduction and stimulates public and private initiatives in research and development, innovation, and other instruments of demand-pull. These advances have shown that the maintenance of carbon-intensive systems is more expansive than the transition to low-carbon systems.

However, beyond the mitigation efforts mentioned above, scientists estimate that the temperature will exceed 1.5ºC in this century and will have difficulty staying below 2ºC (IPCC, 2023), putting the Paris Agreement at risk. Therefore, in addition to mitigation policies, it is essential to implement effective climate adaptation plans.

The main economic impacts of climate change are estimated to be on coastlines, small islands, and mountainous regions, which are more susceptible to floods and landslides. Other areas could be affected by prolonged droughts and have problems with water supply, which also affects food production on land and seafood due to the increase in ocean acidification (IPCC, 2018; 2023). In addition, considering the globalized system, all countries should experience the indirect effects of climate change. According to the World Trade Organization (WTO, 2022), the climate crisis poses future difficulties for the production and trade of goods and services in the world, with the potential to change the entire global trading system. In this scenario, the strategy of reducing the economic and environmental costs associated with trade has been guided by efforts to reduce the emission intensity on trade flows between countries and to implement adaptation strategies as well.

2.2 Emissions and metal ores embodied in trade

Initially, the accounting of national emissions – including the goals of the Paris Agreement – focused on territorial emissions, that is, emissions based on production within borders. However, since the 1990s, with the advancement of production and trade globalization (Baldwin, 2012), the accounting of emissions based on consumption has become even more fundamental (Grubb et al., 2012).

In principle, a country can reduce its territorial emissions through regulation, new technologies, or improved energy efficiency. However, if consumption patterns do not change, the same country could simply allocate emissions to other countries through trade (Wood, 2020). In the literature, the process of allocating the polluting industries by trade is studied as the pollution heaven hypothesis, in which the author analyzes the concentration of polluting industries in developing countries associated with structural, institutional, and trade specialization aspects (Cole, Eliot, 2003; Frankel, 2009; Duan et al., 2021).

In this context, the more intense dynamization of international trade, including trade in intermediate goods and services and global value chains (Gereffi, 2011; Santarcangelo et al., 2017), sheds light on the question of the reduction of emissions intensity and other negative environmental externalities in developing countries and whether this process has contributed to global emissions reduction.

The advance of this discussion pushes the research analysis with metrics that account for the emissions embodied in trade (EEIT). The EEIT metrics account for territorial emissions and consumption emissions, usually referred to as carbon footprint emissions (Steinberger et al., 2012; Grubb et al., 2022). Usually, the methodology that evaluates the emissions on production chains is based on the principles of input-output analysis (Weber; Matthews, 2007; Wiedmann, 2009; Settani et al., 2011), which maps the emissions hotspots on the production structures and sees how the propagation is through sectoral linkages, using the multiregional (MRIO) matrices (Costa, 2021).

In addition, related to the discussion of GHG emissions, the transition to global sustainable power system and clean technologies shed light on the dependence on the acquisition of raw materials and metal ores for its construction (Wiedmann et al., 2015; UNEP, 2011; Hand et al., 2020). On the one hand, the formation of a sustainable power system is important to reduce man-made greenhouse gas emissions and contribute to stopping global warming. On the other hand, the renewable energy infrastructure - such as the construction of solar panels, wind and hydroelectric turbines - increased the global demand of heavy industries, such as mining and metal industries, and increased the GHG emissions.

In this sense, as each economy plays a different role in the mining value chain, the growth of renewable power plants has become a new driver of environmental externalities in a globalised world. Fu et al. (2023) pointed to this discussion, highlighting the inequalities between countries associated with the energy transition process. The results suggest that the rapid transition to low-carbon energy systems in developed countries is conditional on an increase in imports of low-value-added extractive industries in developing countries. Thus, the energy transition process has no net effect on reducing global greenhouse gas emissions.

Therefore, an MRIO analysis also allows us to map the metal footprint embodied in trade, in order to verify the efficient use of metals by nations and the transfer of pollution through global trading systems. It is therefore considered important for policy making to be aware of all the direct and indirect impacts associated with the sustainable energy transition.

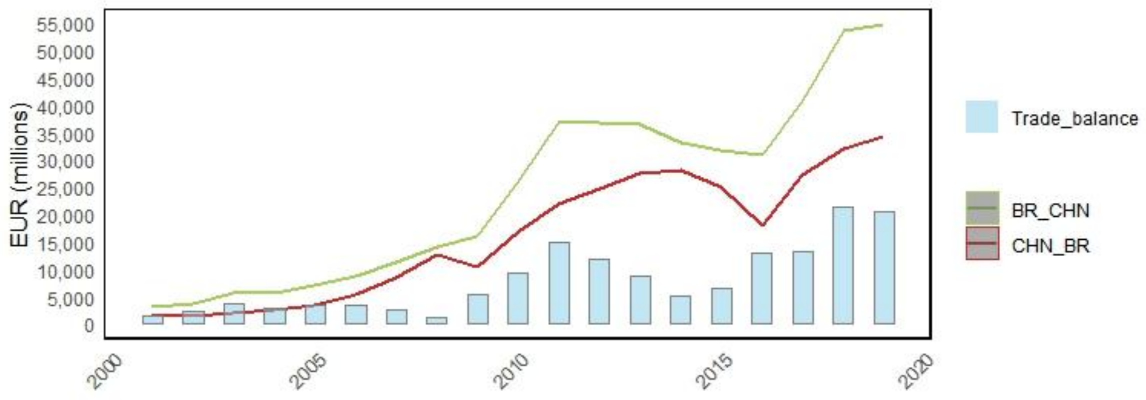
2.3 Bilateral trade of Brazil and China and the ecological unequally exchange

The international trade flows between developing countries usually define the pattern of South-South trade. For Brazil, the South-South pattern is represented by intraregional transactions, with the trade of diversified goods and services with higher shares for capital and technology-intensive goods. For the extra-regional pattern, however, North-South transactions are maintained, with higher shares for raw materials and other manufactured products (Ocampo, Martin, 2004; Bertola, Ocampo, 2012).

International trade between Latin American/Asian countries increases during cold war. Post-war political and economic changes brought new trade opportunities, and East Asia emerged as a strategic region for Brazil's international integration. In 1992, China resumed its development process and in 1993 formalised a strategic trade partnership with Brazil. This partnership preceded China's accession to the World Trade Organization (WTO) and sustained bilateral cooperation through large-scale trade and investment flows (Jenkins, 2012).

In 2009, Asia became the top destination for Brazilian exports and imports. China's role in this transformation has been central: its market share in Brazilian exports increased from 4,2% to 19% between 2002 and 2013, making it Brazil's most important trading partner (Oliveira, 2016). According to the World Trade Integrated Solution (WITS, 2025), China remains Brazil's most important trading partner, accounting for 26.82% of total exports in 2022, while Brazil accounts for only 1.72% of China's total imports in the same year. Figure 1 shows the volume of exports and imports and the trade balance from 2000 to 2020.

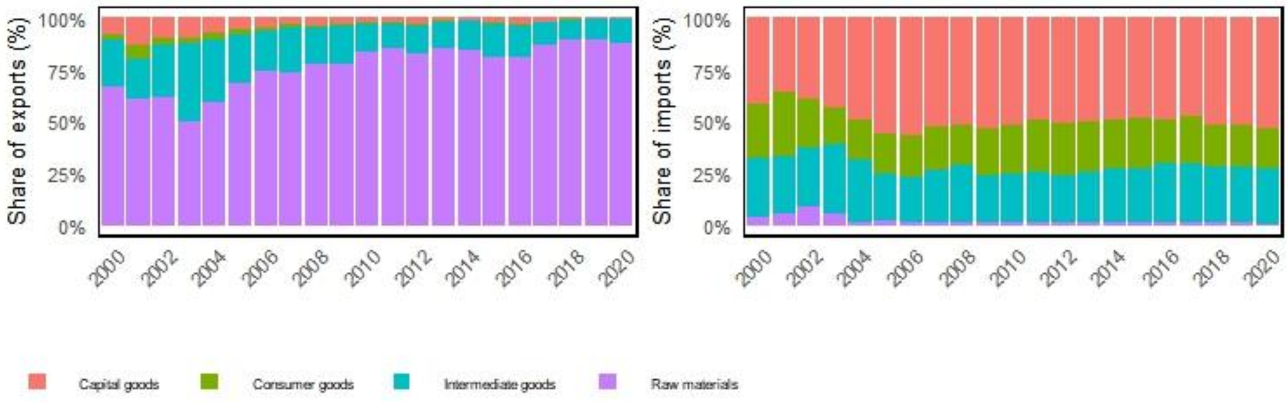
Figure 1 – Exports, imports and trade balance of transactions between Brazil and China (2000 - 2019)



Source: Own elaboration based on EXIOBASE.

Following Figure 1, we pointed out that China's manufacturing growth has a dual effect on Brazil's production structure (Medeiros, 2006). On the one hand, China is Brazil's most important trading partner, becoming a larger supplier of manufactured goods and fundamental to Brazil's trade surplus through higher demand for exports. On the other hand, China's industrial growth affects Brazil's industrial competitiveness, especially in South America (Sennes, Barbosa, 2011). Figure 2 shows the composition of Brazil's exports and imports to China from 2000 to 2020.

Figure 2 – Composition of Brazilian trade flows with China (2000-2020)

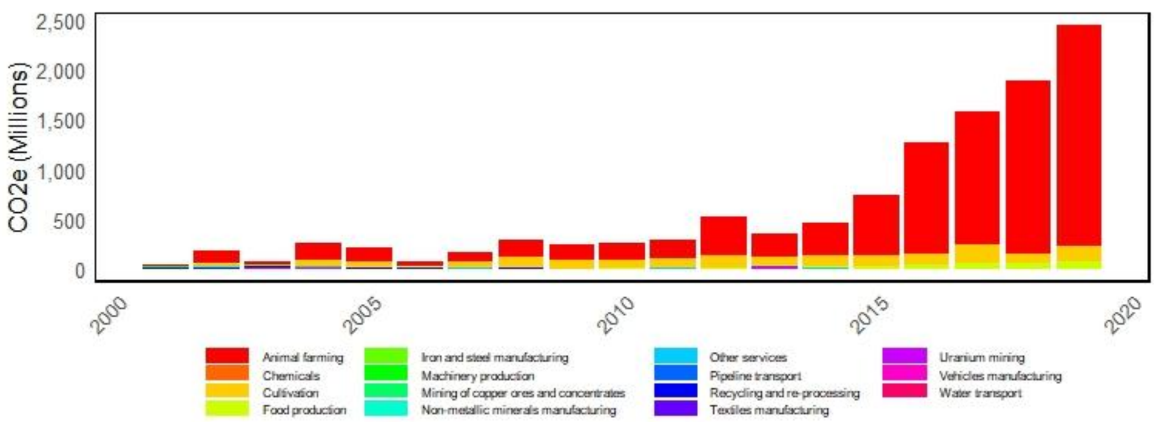


Source: Own elaboration based on WITS.

As shown in Figure 2, the trade partnership between Brazil and China has different characteristics in terms of trade composition. Brazilian exports are concentrated in raw materials with a relatively low level of value-added, while China has a more diversified composition with a higher share of capital goods. In this sense, the composition based on capital and manufactured goods has a positive effect on increasing the value added of Chinese production, favouring industrial and technological development, expanding markets and strengthening the partnership with South American countries. Bilateral trade between Brazil and China therefore involves many economic interests that define this partnership.

Moreover, this trade pattern has affected the structure of Brazilian exports (Bertola, Ocampo, 2012), with direct and indirect implications for the environmental dimension. Figure 3 shows the sectoral composition of Brazilian GHG emissions embodied in exports to China from 2000 to 2019.

Figure 3 – GHG emissions of Brazil's exports to China (2000-2019)

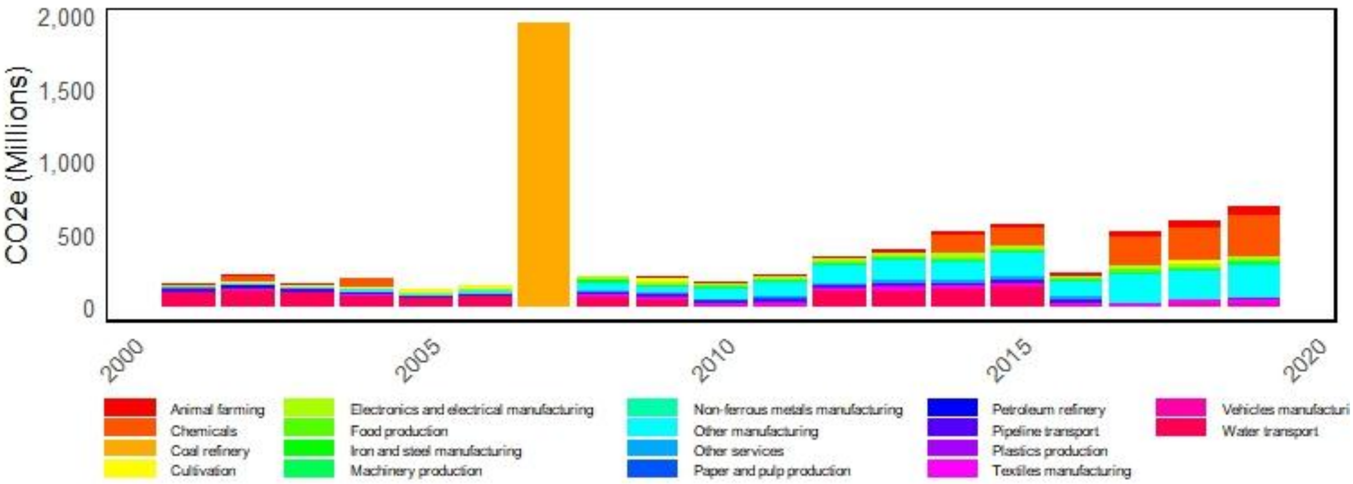


Source: Own elaboration based on EXIOBASE.

As shown in Figure 3, the GHG emissions embodied in exports follow the same trend as the trade composition pattern based on commodity industries, with livestock, crop, and food production dominating. GHG emissions from animal husbandry activities usually represent methane gas emissions caused by enteric fermentation in animal husbandry. However, emissions from the livestock sector are also linked to emissions from land-use change in Brazil. The expansion of agricultural activities in the Brazilian territory has been responsible for the increase in illegal deforestation of native forests, which affects the Amazon and Cerrado biomes the most (Pereira, 2020; Potenza et al., 2021). In this state, Brazil has been one of the main contributors to the increase in global greenhouse gas emissions (Potenza et al., 2021) associated with deforestation (Gutschow et al., 2016).

Figure 4 shows the evolution of emissions embodied in exports from China to Brazil. The manufactured industries – representing the Other manufacturing, Vehicle manufacturing, Chemicals, and Water transport – were the sectors with higher rates of emissions in exports to Brazil. The exception was in 2007 when the Coal refinery represented almost all the total emissions delivered to Brazil.

Figure 4 – GHG emissions of China's exports to Brazil (2000-2019)



Source: Own elaboration based on EXIOBASE.

This composition shows the weight of the industrial sectors in China's GHG emissions. China's industrial development has intensified throughout this century, with impressive results. Territorial expansion is an important factor that has driven the diversification of local production, in line with regional integration objectives to consolidate the largest global production of electronic products in China (Medeiros, 2006). However, Bloch et al. (2015) show that China's economic growth has been supported by non-renewable energy sources, mainly coal and oil, from the demand and supply side, making China's production with higher emission intensity rates.

Thus, as shown in Figure 3, China's productive diversification can be translated into an increase in GHG emissions from the industrial sector, which is embodied by consumption in Brazil. However, if we compare Figure 2 with Figure 3, we see that the emission level of China's exports to Brazil is lower than that of Brazil's exports to China. This could be due to differences in trade volume - with the higher volume of Brazilian exports corresponding to more emissions traded - but also to the composition of trade.

Therefore, we can observe that the pattern of GHG emissions and trade between Brazil and China shows a "North-South" pattern (Bertola, Ocampo, 2012), but between developing countries, with Brazil being the largest raw material exporter and China the industrial exporter. Klink et al. (2024) analyzed the relationship between Brazil and China in terms of land use, water withdrawal, and greenhouse gas emissions from 1995 to 2020. The results confirm that there is an increasing unequal exchange of biophysical resources flowing from Brazil to China to achieve larger Chinese socio-economic goals. In this state, many studies have pointed to the role of China in the ecologically unequal exchange (EUE), which has become a net importer of biophysical components from developing countries (Yu et al., 2014; Mol, 2011), while remaining a net exporter with developed countries (Davis and Caldeira, 2010; Dorninger et al., 2021).

The EUE studies the socioecological effects associated with international trade patterns between countries and regions. The core of the EUE theory argues about the environmental and social costs embedded in economic activities that are not fully captured by monetary terms in international trade transactions (Hornborg, 1998). In this approach, the environmental and social costs are represented by biophysical indicators – such as greenhouse gas emissions, land area used, volumes of water, volumes of materials, energy intensity, labor, etc. – that emphasize the variety of pressures driven by international trade position (Hornborg, 2023; Klink et al., 2024). In a historical sense, the economic growth and development of North countries were conditioned on the exchange with developing countries, mainly through the demand for raw materials (Prebish, 1973; Fajnzylber, 1988; Baer, 2011; Saez, 2023). In this position, the developing countries' debt of ecological resources is seen as another face of inequality caused by the asymmetric relationship in the world system.

Therefore, the EUE research[1] provides evidence on the extended environment (EE MRIO) to investigate international trade patterns and translate the international relationship through biophysical components. This evidence is considered most important because it allows us to measure the impact of trade in various dimensions, as well as to discuss responsibilities (Lenzen and Murray, 2010, Zhang et al., 2020) and the transfer of environmental externalities in a complex and globalised world system.

3 Methodology

Greenhouse gas emissions embodied in trade

This study proposes an input-output analysis to investigate the carbon dioxide emissions associated with the bilateral trade pattern of Brazil, China and the rest of the world. Initially, we considered the basic production function of Leontief (1936), defined as:

$$\mathrm{x} = (\mathrm{I} - \mathrm{A})^{-1}\mathrm{y} = \mathrm{Ly}, \qquad (1)$$

where $\mathrm{L} = (\mathrm{I} - \mathrm{A})^{-1}$ is the Leontief inverse matrix or total or total demand matrix, which takes into account the direct and indirect inter-sectoral effects on production. In this sense, the fundamental of the model is that the total production x is determined by the intermediate consumption as a fixed proportion of the value of production, given by the technical coefficient A, and the demand variations y (Miller, Blair, 2009).

Thus, considering the trade flows between Brazil and China, we can measure the CO2e emissions generated to the direct and indirect final consumption of these countries in equations (2) and (3), respectively.

$$TC_{Bra} = [e_B \; e_C \; e_R] \begin{bmatrix} L_{B-B} & L_{B-C} & L_{B-R} \\ L_{C-B} & L_{C-C} & L_{C-R} \\ L_{R-B} & L_{R-C} & L_{R-R} \end{bmatrix} \begin{bmatrix} Y_{B-B} \\ Y_{C-B} \\ Y_{R-B} \end{bmatrix} =$$
$$= (e_B L_{B-B} + e_C L_{C-B} + e_R L_{R-B})Y_{B-B} + (e_B L_{B-C} + e_C L_{C-C} + e_R L_{R-C})Y_{C-B} + (e_B L_{B-R} + e_C L_{C-R} + e_R L_{R-R})Y_{R-B} \quad (2)$$

$$TC_{Chn} = [e_B \; e_C \; e_R] \begin{bmatrix} L_{B-B} & L_{B-C} & L_{B-R} \\ L_{C-B} & L_{C-C} & L_{C-R} \\ L_{R-B} & L_{R-C} & L_{R-R} \end{bmatrix} \begin{bmatrix} Y_{B-C} \\ Y_{C-C} \\ Y_{R-C} \end{bmatrix} =$$

[1] See Dorninger and Hornborg (2015).

$$= (e_B L_{B-B} + e_C L_{C-B} + e_R L_{R-B}) Y_{B-B} + (e_B L_{B-C} + e_C L_{C-C} + e_R L_{R-C}) Y_{C-C} + (e_B L_{B-R} + e_C L_{C-R} + e_R L_{R-R}) Y_{R-C} \quad (3)$$

The acronyms "Bra" and "B" meaning Brazil; "Chn" and "C" China; and "Row" e "R" the Rest of the World, i.e all countries excluding the Brazil and China. The inverse Leontief matrix, L, is a square matrix divided into nine parts; Y is the final demand vector; and e is the emissions coefficient, given by $e = C/X$, where C is the sectoral CO2e emissions and X the sectoral total production. Therefore, the TC equations accounting for total CO2e emissions generated by the final consumption, domestic and foreign, of countries analysis.

To account for CO2e total emissions embodied only in exports:

$$EC_{Bra-Chn} = [e_B \; 0 \; 0] \begin{bmatrix} L_{B-B} & L_{B-C} & L_{B-R} \\ L_{C-B} & L_{C-C} & L_{C-R} \\ L_{R-B} & L_{R-C} & L_{R-R} \end{bmatrix} \begin{bmatrix} Y_{B-C} \\ Y_{C-C} \\ Y_{R-C} \end{bmatrix} =$$

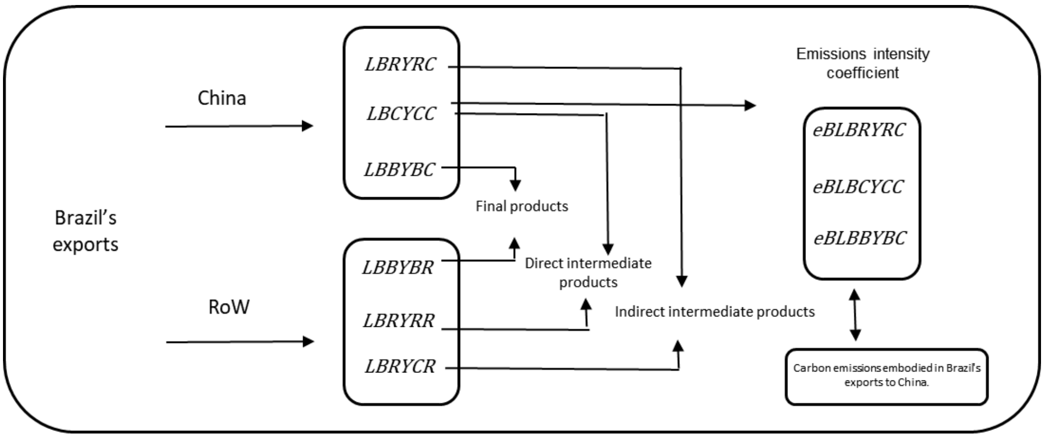
$$= e_B L_{B-B} Y_{B-C} + e_B L_{B-C} Y_{C-C} + e_B L_{B-R} Y_{R-C} \quad (4)$$

$$EC_{Chn-Bra} = [0 \; e_C \; 0] \begin{bmatrix} L_{B-B} & L_{B-C} & L_{B-R} \\ L_{C-B} & L_{C-C} & L_{C-R} \\ L_{R-B} & L_{R-C} & L_{R-R} \end{bmatrix} \begin{bmatrix} Y_{B-B} \\ Y_{C-B} \\ Y_{R-B} \end{bmatrix} =$$

$$= e_C L_{C-B} Y_{B-B} + e_C L_{C-C} Y_{C-B} + e_C L_{C-R} Y_{R-B} \quad (5)$$

where, $EC_{\text{Bra-Chn}}$ is the CO2 emissions embodied in the Brazil's exports to China, while $EC_{\text{Chn-Bra}}$ is the emissions on China's exports. The CO2 emissions embodied in exports can be decomposed direct ($e_B L_{B-B} Y_{B-C}$) or indirect ($e_B L_{B-C} Y_{C-C}$) emissions. Figure 4 shows the flux diagram of the accounting method.

Figure 4 – Directly and indirectly emissions on Brazil's exports



Source: Own elaboration.

As seen in the Figure 4, in the emissions in exports from Brazil to China ($EC_{\text{Bra-Chn}}$), there may be some goods that are first processed by Brazil and then exported to other countries, except China. However, after re-processing, these countries could export the final goods to China, which is common for transactions in GVCs. Thus, all CO2e emissions generated by Brazil's exports to China are considered.

Therefore, based on the emissions embodied in exports, net exports can be measured in CO2:

$$NEC = EC_{Bra-Chn} - EC_{Chn-Bra} \quad (6)$$

The *Net Exports Carbon* (NEC) represent the net CO2e emissions embodied in exports. If NEC > 0, means that the Brazil has a CO2e surplus embodied on exports to China, otherwise, if NEC < 0, thus Brazil has a CO2e emissions deficit in this trade. The net export carbon can be influenced by the trade balance, in volume, and also for the energy matrix and the position of the country in the international division of labor (Grubb et al., 2022).

Finally, following the same principles, we can aggregate CO2e emissions from international trade for each country:

$$EC_{Bra-RoW} = [e_B \; 0 \; 0] \begin{bmatrix} L_{B-B} & L_{B-C} & L_{B-R} \\ L_{C-B} & L_{C-C} & L_{C-R} \\ L_{R-B} & L_{R-C} & L_{R-R} \end{bmatrix} \begin{bmatrix} Y_{B-C} + Y_{B-R} \\ Y_{C-C} + Y_{C-R} \\ Y_{R-C} + Y_{R-R} \end{bmatrix} =$$
$$= e_B L_{B-B}(Y_{B-C} + Y_{B-R}) + e_B L_{B-C}(Y_{C-C} + Y_{C-R}) + e_B L_{B-R}(Y_{R-B} + Y_{R-R}) \quad (7)$$
$$EC_{Chn-RoW} = [0 \; e_C \; 0] \begin{bmatrix} L_{B-B} & L_{B-C} & L_{B-R} \\ L_{C-B} & L_{C-C} & L_{C-R} \\ L_{R-B} & L_{R-C} & L_{R-R} \end{bmatrix} \begin{bmatrix} Y_{B-B} + Y_{B-R} \\ Y_{C-B} + Y_{C-R} \\ Y_{R-B} + Y_{R-R} \end{bmatrix} =$$
$$= e_C L_{C-B}(Y_{B-B} + Y_{B-R}) + e_C L_{C-C}(Y_{C-B} + Y_{C-R}) + e_C L_{C-R}(Y_{R-B} + Y_{R-R}) \quad (8)$$

where all CO2e emissions, direct and indirect, are generated by external demand are considered. Therefore, this metric provides an aggregated view of territorial emissions generated for the international market.

Metal footprint in renewable power value chains

To estimate the metal footprint (MF) in global production chains we considered the classical Leontief production system. First, we defined the metal footprint coefficient as:

$$m = \left\{ \frac{m_i^s}{x_i^s} \right\} \qquad (9)$$

where m is a vector of the direct metal consumption extracted per unit of total output of sector i in economy s. Thus, considering the technical coefficient matrix A, where each element a_{ij}^{sr} demonstrate the intermediate inputs of sector i in economy s to produce one unit of output in sector j in economy r, we derived the global inverse of Leontief, $\mathrm{B} = (\mathrm{I} - \mathrm{A})^{-1}$, which captures the direct and indirect inputs to determine the output. With a focus on observing the MF associated with the production of electricity via renewable power value chains, the demand vector $Y$is composed only of the renewable power sector's demand, attributing zeros for the other sectors. Therefore, based on Fu et al. (2023), the MF embodied in all goods and services to produce electricity from renewable power sources could be mathematically expressed as:

$$\widehat{m}\mathrm{BY} = \begin{bmatrix} m_{nele}^s & 0 & \cdots & 0 \\ 0 & m_{ele}^s & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & m_{nele}^r \end{bmatrix} \times \begin{bmatrix} b_{nele,nele}^{ss} & b_{nele,ele}^{ss} & b_{nele,nele}^{sr} & b_{nele,ele}^{sr} \\ b_{ele,nele}^{ss} & b_{ele,ele}^{ss} & b_{ele,nele}^{sr} & b_{ele,ele}^{sr} \\ b_{nele,nele}^{rs} & b_{nele,ele}^{rs} & b_{nele,nele}^{rr} & b_{nele,ele}^{rr} \\ b_{ele,nele}^{rs} & b_{ele,ele}^{rs} & b_{ele,nele}^{rr} & b_{ele,ele}^{rr} \end{bmatrix} \times \begin{bmatrix} 0 & 0 \\ y_{ele}^{ss} & y_{ele}^{sr} \\ 0 & 0 \\ y_{ele}^{rs} & y_{ele}^{rr} \end{bmatrix} (10)$$

Where $\widehat{m}$ is a diagonal matrix of m coefficient and the subscript ele is for the electricity sectors and $nele$ is non-electricity sectors. Therefore, the equation (10) could also be express as follows:

$$MF_{ele}^s = \sum_{r \neq s}^{N} (\widehat{m}^r B^{ss} y^{ss} + \widehat{m}^r B^{rs} y^{ss} + \widehat{m}^r B^{rr} y^{rs} + \widehat{m}^s B^{sr} y^{rs}) \quad (11)$$

Thus, according to Xu and Dietzenbacher (2014), we can write the metal footprint embodied in exports (MEE) as:

$$MEE^r = \sum_{s \neq r}^{N} (\widehat{m}^r B^{rr} y^{rs}) + \sum_{s,k \neq r}^{N} (\widehat{m}^r B^{rr} y^{rk}) \quad (12)$$

where the first part represents the metals embodied in economy r's renewable power export that are consumed in economy s, and the second part is the metal embodied in economy r's intermediate sectors, that are exported and used by renewable power for all other k economies.

Analogue, the metal footprint embodied in imports (MEI) is given as:

$$MEI^{r} = \sum_{s,k\neq r}^{N} (\hat{m}^{k} B^{ks} y^{sr}) + \sum_{s\neq r}^{N} (\hat{m}^{s} B^{sr} y^{rr}) \quad (13)$$

where the first part is the global metal footprint embodied by economy s to produce in renewable sector and consumed in the economy r, and the second part is the metal embodied in intermediate inputs imported by economy r to produce renewable electricity. Therefore, based on MEE and MEI accounting it is possible to map the metal footprint in international trade associated with renewable power systems.

3.1 Database

EXIOBASE version 3 is an environmentally extended multi-regional input-output (EE MRIO) database with high suitability for environmental analysis. The tables range from 1995 to 2011 - but with various nowcasts to extend the data to 2022 - for 44 countries (28 EU Member States plus 16 major economies) and five rest of the world regions, 163 industries and 200 commodities. The data provides a consistent framework for tracking emissions, resource use and other biophysical components along supply chains, thus linking consumption patterns to production processes elsewhere (Stadler et al., 2018). We select the data for Brazil and China, and all the other countries were aggregated as Rest of the World (ROW), for the period 2000 to 2019.

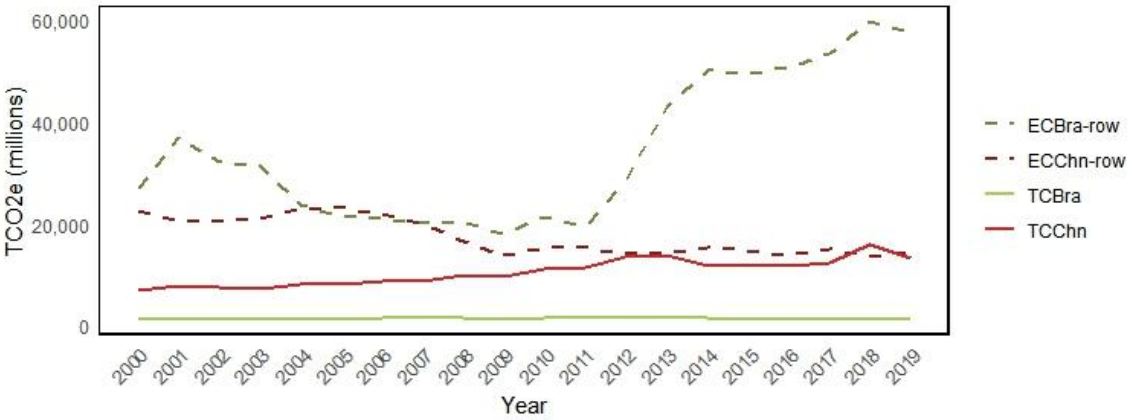
For the GHG emissions data, we selected the main gases responsible for global warming: carbon dioxide (from combustion, agriculture, peat decomposition, biogenic and fossil waste), methane (from combustion, agriculture and waste) and nitrous oxide (from combustion and agriculture). The data are expressed in units of kilograms (kg) of carbon equivalent (CO2e) according to the Global Warming Potentials (GWP) provided by the Intergovernmental Panel on Climate Change (IPCC, 2023).

For the metal footprint analysis, according to Fu et al. (2023), we select the crucial metal ores in demand in renewable power sectors, considering the Hydroelectric power plants, Wind farms, and Solar power plants. The metals were aggregated into four categories: bulk metal ores (bauxite, copper, iron, lead, and zinc ores), precious metal ores (silver and platinum group metal ores), scarce metal ores (nickel and tin ores) and other non-ferrous metal ores, which are express in kilotons units (UNEP, 2011).

4. Analysis discussion

First, there is a discussion on the amount of GHG emissions produced by Brazil and China for the supply of domestic and foreign markets. Figure 5 shows the GHG emissions associated with the direct and indirect final consumption of Brazil (TCBra) and China (TCChn), as well as the countries' territorial emissions for foreign consumption (ECBra row and ECChn row).

Figure 5 – GHG emissions embodied in direct final consumption (TC) and international trade



Source: Own elaboration based on EXIOBASE.

For emissions embodied in total consumption (TC), Figure 5 highlights that China has a higher level of GHG emissions than Brazil all long the period. As the indicator measures all the emissions that are generated domestically and foreign in intermediate input processing and final consumption, its results suggest the differences in productive structure and global market share of those countries. China is considered one of the largest energy consumers in the world, with the highest dependence on coal to produce electricity, second global consumer in oil, and fourth for natural gas (Oliveira et al. 2020), which makes China an intensive pollution consumer. Brazil is also a larger consumer of energy and has an urban and industrial density that contributes to the increase in emissions (Oliveira, 2020). However, due to the availability of renewable energy[2], the Brazilian productive structure is considered low carbon compared to OECD economies and other developing countries (OECD, 2015).

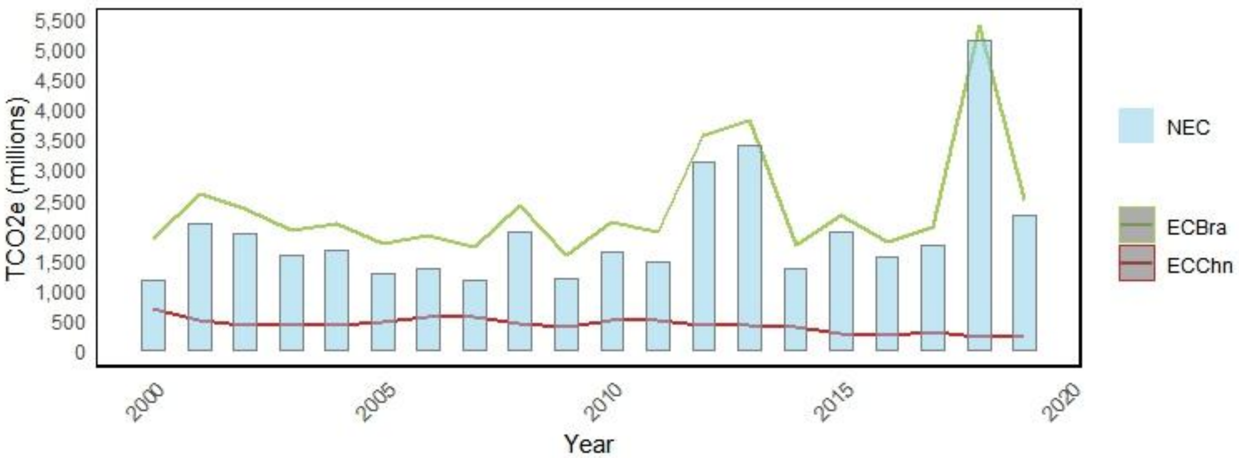
For territorial emissions for international trade - i.e. production-related emissions within countries' borders - we see a different trend in emissions. The results show that China is able to reduce emissions embodied in exports, while Brazil maintains a higher level and shows a significant increase after 2011. The results suggest that China's industrial upgrading could be associated with the reduction of emissions in Chinese final exports (Li et al., 2022). For Brazil, the results indicate that exports based on raw materials and commodities, which represent almost 15% of total world trade (Montoya et al., 2021), are associated with the increase in Brazilian GHG emissions over this period[3]. Therefore, the results suggest the Chinese sectors have been more consumption-based emissions-intensive, while Brazil has been production-based emissions-intensive.

Figure 6 shows the GHG emissions embodied with exports from Brazil to China and the net emissions carbon (NEC) indicators. Firstly, these results show that the level of emissions is related to the volume of exports, so it is possible to see some correspondence with Figure 1.

[2]According to IEA (2020), in 2015, 47.5 percent of Brazil's total energy consumption came from renewable sources (mainly hydro, ethanol, and wind), while non-renewable sources (diesel, oil, and natural gas) accounted for 52.45 percent.

[3] In 2009, Brazil enacted the National Climate Change Policy (PNMC), through Law No. 12.187 (BRASIL, 2009), which set ten targets to reduce greenhouse gas emissions, including targets to reduce deforestation, improve energy distribution and efficiency, and mitigate and adapt to climate impacts. In the SEEG (2021), the analysis of the previous period of the PNMC, between 2009 and 2020, shows that despite the achievement of some of the targets set - notably the 38.6 percent reduction in emissions by 2020 - the implementation of the targets was uncoordinated and did not contribute to a change in Brazil's emissions trajectory.

Figure 6 – GHG emissions embodied in exports and NEC indicator: Brazil and China

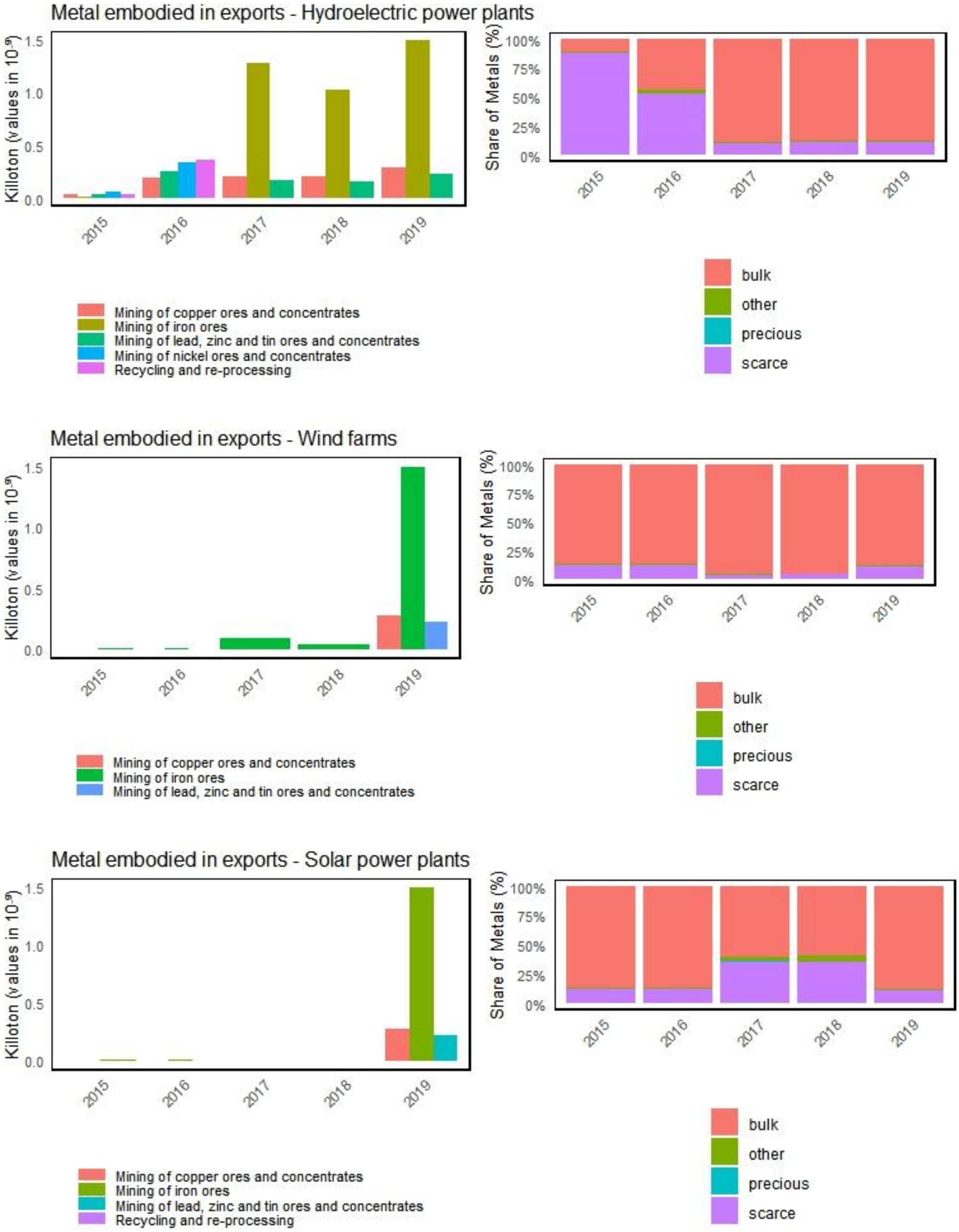


Soruce: Own elaboration based on EXIOBASE.

As shown in Figure 6, Brazil's trade surplus with China is fully translated into a surplus in terms of GHG emissions (NEC > 0). In other words, Brazil has accumulated emissions on trade with China, producing more emissions than are consumed in this trade relationship. It is indicated that there exists an outflow of Brazilian emissions to attend to the Chinese demand, as pointed out by Klirk et al. (2024). Therefore, the pattern of bilateral trade between Brazil and China has demonstrated convergence with the ecologically unequal exchange approach findings, reproducing a kind of core-peripheral relationships among developing countries.

Furthermore, we are analyzing the metal footprint embodied in trade to the renewable power sector of Brazil to the world. Figure 7 presents the metal ores embodied in exports (MEE) for Hydroelectric power plants, Wind farms, and Solar power plants from 2015 to 2019. In general, for the three renewable power sources, the metal embodied in Brazil’s exports is from the mining of iron, copper, lead, zinc, tin, and concentrates, which represent the bulk and scarce metal ore groups. Moreover, noticing the increasing metal footprint all along this short period suggests the increased global demand for renewable and clean technologies. Its results indicated that Brazil’s role in the renewable power supply chains is predominant in the mining stages. According to Fu et al. (2023), developing countries, such as Latin America, Africa, and some Asia countries, represent more than half of metal ores embodied in trade.

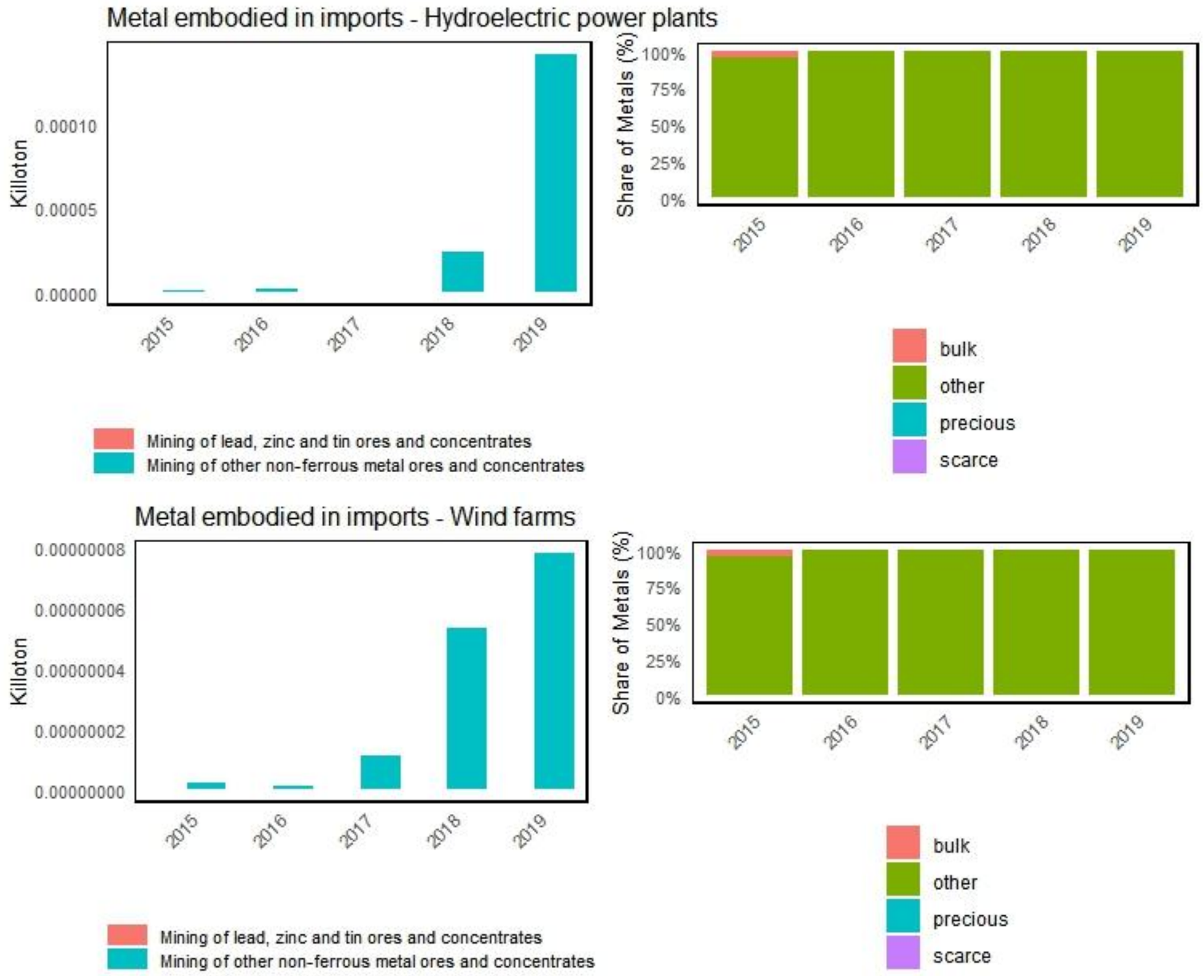
Figure 7 – Metal embodied in exports of Brazil to the renewable power sector



Source: Own elaboration based on EXIOBASE.

Figure 8 presents the metal ores embodied in imports (MEI) of Brazil to the renewable power sector. The Brazilian demand for renewable value chains comes from other non-ferrous metal ores – such as aluminum, manganese, chrome, etc. – to the Hydroelectric and Wind farms. In the analysis period, the Solar Power Plants did not present expressive results for metal ores imports. It results correlate with the composition of Brazil's energy matrix, which has hydropower as important representative sources of renewable electricity (IEA, 2020).

Figure 8 – Metal embodied in imports of Brazil to renewable power sector



Source: Own elaboration based on EXIOBASE.

Therefore, based on the results, the expressive participation of the extractive sectors in Brazil's exports indicates potential challenges to reducing the material footprint. That is because these sectors are considered the greater generated of negative environmental externalities and are also complex to mitigate, due to the sunk cost of infrastructure and the nature of the process (Grubb et al., 2022). Some ways to improve material efficiency, such as design optimization, scale, and material substitution (Fu et al., 2023). However, given Brazil's subordinate role in the world trading system, the country should maintain its status as a net exporter of biophysical resources.

5. Final considerations

In this paper, we analyze the pattern of GHG emissions and material footprint in renewable power plants associated with the bilateral trade pattern between Brazil, China, and the Rest of the World from 2000 to 2019. Through an input-output applied to the EXIOBASE MRIO, we estimate the emissions embodied in goods and services of 56 sectors. This type of analysis is important because it allows for measuring the trade relations in terms of biophysical indicators, also identifying the sectors more intensive in GHG emissions and metal ores; mapping the transference of pollution on international trade and globalized production, and, finally, driving the better trade policy in the context of the climate crisis. Further, the discussion interacts with the ecologically unequal exchange theory, in order to observe the socioecological costs embodied in trade between different nations and regions.

In general, the results show that bilateral trade between Brazil and China follows a North-South pattern, with Brazil being the larger supplier of raw materials and commodities, and China being the larger supplier of industrialized and higher value-added goods and services. The trade pattern is reproduced on the environmental dimension, where agriculture and food production are more CO2e-intensive in Brazil's exports to China, while manufacturing, machinery and equipment are more CO2e-intensive in China's exports to Brazil.

In the total consumption emissions indicator (domestic and foreign) and emissions on international trade (foreign), we observed that Brazil was a greater production-based emissary, while China evolved to a consumption-based with developing economies. In this sense, the results of Net Emissions Carbon demonstrate that Brazil has had a surplus of GHG emissions on its transactions with China. This result is related to the export volume, the energy efficiency, and the emission intensity of Brazil's export structure.

Finally, in the material footprint analysis, the results indicate that Brazil's role in renewable electricity value chains is in the mining stages, in the categories of bulk and scarce metal ores. On the one hand, these sectors are positively affected by the low-carbon electricity system, which requires more material components than fossil-fuel electricity. On the other hand, the mining sectors generate the largest number of negative environmental externalities.

Therefore, based on this analysis and considering the strategic partnership between Brazil and China, we pointed out the principle of shared responsibility (Rodrigues et al., 2006; Zhang et al., 2020) as a reference to design trade policies for these countries. The principle of shared responsibility is the only one able to take into account the indirect effects of emissions and material embodied in international trade and stimulate mutual benefits for these countries. In this sense, we understand that it is possible to align the policy design in bilateral trade with the goals of emissions compensation - for example, through technology transfer, investment in emissions reduction plans, incentives for research and development, innovation, etc. - using MRIO accounting as an instrument. These considerations reinforce the need to maintain a holistic perspective on policy design in the context of climate change.

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