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Reducing GHG global emissions from copper refining and sea shipping of Chile's mining exports: A world win-win policy☆

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ABSTRACT

Chile is the largest copper producing country of the world; and almost 50% of the copper it exports to the rest of the world is exported as copper concentrates to be smelted and refined abroad. However, 70% of the weight of these exported copper concentrates is gangue (valueless and undesirable material associated to the copper content in these exported concentrates). In this paper analyze and quantify the contribution Chile could make to the ongoing world efforts to reduce climate change and global warming, if it adopts a trading policy eliminating its exports of copper concentrates and replacing them with the greater value added exports of the refined copper obtained from smelting and refining those concentrates in Chile. This policy would allow a significant reduction of greenhouse gases (GHG) emitted every year to the global atmosphere. This reduction would occur through two channels: 1. avoiding the combustion of more than 600,000 tons of diesel oil currently used to transport by sea almost 6,600,000 tons of the gangue incorporated in Chile's copper concentrate exports; and, 2. using Chile's cleaner technology for smelting and refining copper concentrates instead of the dirtier technologies of the countries currently importing, smelting and refining the Chilean copper concentrates. For the first time, using data for 2014, we estimate the total net reduction in GHG emissions to the global atmosphere that the proposed trade policy would imply. We calculate the distance of the nautical routes used for the 919 shipments of concentrates exported by Chile that year; and we perform sensitivity analysis for 4 scenarios, employing two alternative values for two key parameters. Additionally, we compare the GHG emission performances of the copper smelting and refining metallurgic technologies employed in Chile and in every one of the 22 countries that import and smelt and refine Chilean concentrates. Our estimates for the 2 most extreme scenarios indicate that, if instead of exporting copper concentrates in 2014, Chile would had exported only refined copper, it would had contributed with a total net reduction of GHG emissions emitted to the global atmosphere of 2,227,047 and 2,799,279 ton CO2-eq tons that year, which are equivalent to approximately 5.6% of the total amount of GHG emissions that would had made Chile fully carbon neutral that year. This is a significant contribution regarding Chile's commitment to the Paris Agreement as well as in terms of the required world efforts to reducing GHG emissions from sea shipping.

1. Introduction

Chile is the largest copper producing country; in the last 10 years, it produced 30% of all the copper produced in the world (Cochilco, 2018). A significant portion of the copper exported from Chile is not refined copper. This portion is exported in the form of copper concentrate, an intermediate material resulting from an initial ore mine extraction, and processed afterwards through crushing, flotation, thickening and filtering, and which contains around 30% of copper, plus other minerals and, mostly, gangue (valueless and undesirable material). As an intermediate good, copper concentrate is destined to be processed later on through a set of metallurgic processes required to obtain a product with

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more than 99% of copper[1] (Cochilco, 2016).

In 2014, Chile exported the equivalent to 5.8 million tons of refined copper, and almost 2.8 million of them, or 49%, were exported as copper concentrate and the other 3.0 million as refined copper.[2] Table 1 shows the shares of refined copper and copper concentrates in Chile's total copper exports for the last decade, and for 2014 in particular (the most recent year for which the required data for our key estimations is available). In the early years of the last decade, the participation of copper concentrates in total copper exports was 41%, and it rose up to 47% by 2015.

As it is shown in Table 1, during the 2006–20015 period, 40% of Chile's copper exports in terms of its refined copper equivalent were exported in the form of copper concentrates. However, in the last lustrum this share has increased and currently is more than 50%. Copper concentrate contains between 20% and 40% copper (Central Bank of Chile, 2015), with an average of 30% copper in 2014. The millions of tons of copper metal exported in the form of copper concentrate every year, 9,385,444 tons in 2014, are shipped from Chile to the importing countries accompanied by around 2.4 times its weight of gangue (mostly valueless materials and a small percentage of other ores which is not relevant to this study). This overload weight would not be transported if copper was exported in the form of refined copper instead of copper concentrates.

In 2014, 919 shipments of copper concentrate were sent from 13 Chilean ports to 22 foreign countries (Central Bank of Chile, 2015). The total direct nautical distance travelled by the freight-ships transporting these shipments was over 15.5 million kilometers (around 9.6 million miles), which is equivalent to 40.3 times the distance between the Earth and the Moon. Moreover, during the entire last decade, the ships that carried those millions of tons of gangue over such huge distances burned millions of barrels of diesel oil every year. As a result, millions of tons of greenhouse gases (GHG) were produced and released into the atmosphere and, according to IPCC (2014), they contributed to the ongoing climate change and global warming.

In fact, there is a scientific consensus on the impact that the GHG concentrations in the atmosphere cause on global physical processes and their implications on rising temperature and changing other climate variables (Levitus et al., 2009; IPCC, 2014). The IPCC has reported that, with 95% confidence, the increase of carbon emissions resulting from human activities worldwide has had, and will continue to have, harmful consequences to the planet; including: sea level rise, more frequent and severe natural disasters (mega droughts, floods, wildfires) and reduced water availability for human consumption and relevant economic activities (IPCC, 2014).

Table 1
Chile: Shares of exported refined copper and copper concentrates in total exported copper; 2014 and 2006–2015 average.

TYPE OF COPPER PRODUCT	SHARE OF TOTAL EXPORTED REFINED COPPER EQUIVALENT	
	2014	2006–2015 AVERAGE
	(%)	
Refined copper	51	60
Copper concentrate	49	40

Source: Own estimations using information from Cochilco (2016)

Several scientific studies have warned that global warming of more than 1 °C, relative to 2000, will constitute "dangerous" climate change as judged from likely effects on sea level and extermination of species (Hansen et al., 2006). Regardless of these warnings, in 2009, the OECD had already projected that without new policy actions world GHG emissions would increase by about 70% by 2050 and continue to grow thereafter. This could lead to a rise in world temperatures of 4 °C above preindustrial levels, and possibly 6 °C, by 2100 (OECD, 2009). This would have large implications for the planet; it would cause a significant destruction of the habitats of plants and animals and yield reductions of important food crops, and large numbers of people will be exposed to severe droughts and floods (Hansen et al., 2012, 2010a,b,c; Schmidt et al., 2014; IPCC et al., 2007).

Moreover, the most recent IPCC studies have warned that estimated anthropogenic global warming is currently increasing at 0.2 °C per decade due to past and ongoing emissions; that, warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic; and that, warming is generally higher over land than over the ocean (IPCC, 2018). Just in September 2019, IPCC (2019) reported that it is virtually certain that the global ocean has warmed unabated since 1970 and that, with high confidence, it has taken up more than 90% of the excess heat in the climate system. This reports also warns that, since 1993, the rate of ocean warming has likely more than doubled, and marine heatwaves have very likely doubled in frequency since 1982 and, with very high confidence, they are increasing in intensity. Additionally, with almost certainty, the ocean has undergone increasing surface acidification, as result of absorbing more CO2. These studies had indicated also that, with high confidence, climate-related risks for natural and human systems are higher for global warming of 1.5 °C than at present, but lower than at 2 °C. Also that, these risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (IPCC, 2018). The best scientific projections currently available indicate, with medium confidence, that by 2100, global mean sea level rise will be around 0.1 m lower with global warming of 1.5 °C compared to 2 °C, and that, with high confidence, sea level will continue to rise well beyond 2100, and the magnitude and rate of this rise depend on future emission pathways. IPCC (2019) informs that a slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas.

All this evidence is indicating that reducing GHG emissions and its concentrations in the planet's atmosphere is an urgent challenge that must be met, which implies that to achieve the Paris climate objectives of limiting the increase of global mean temperature to well below 2 °C requires today, among other measures, drastic changes in energy systems (Van Vuuren et al., 2017), global maritime shipping (Broder and Van Dike, 2017; Rahim et al., 2016) and aviation transport (Bows-Larkin, 2015). In fact, according to IPCC (2019), enabling climate resilience and sustainable development depends critically on urgent and ambitious emissions reductions, as well as on intensifying cooperation and coordination among governments. Emphasis is given to prevent and reduce emissions, in which Chile can and must take a specific responsibility (OECD, 2013). In this context, our estimates in this work are relevant, as they quantify a significant source of GHG emissions from Chile's mining sector being emitted to the global atmosphere that may be eliminated. Refining copper in Chile is a contribution that the country is able and could do for the sake of the planet. In addition, as it is argued below, in the future, this may enable Chile to fulfill its international commitments to tackle global warming.

Here we do not analyze the reasons why not all copper concentrates are refined in Chile; but several authors agree in that there are no technical or economic reasons explaining this (Correa, 2016; Dulanto, 1999)). Moreover, prior to the last boom in copper prices (2004–2016),

[1] These processes are basically transportation, smelting and thermal and electrochemical processes to get the desired final product: refined copper. In this work, every time copper refining is mentioned, this chain of processes is being referred.

[2] For the purposes of this work, refining involves collecting cathodes made of 99.9% copper from electrochemical processes and the so-called blister copper (i.e. smelted copper that undergoes fire-refining in a furnace) which is made of 99.4% copper.

other authors were emphatic in pointing out that all copper exported from Chile must be domestically refined as a matter of a wise economic development policy (Dulanto, 1999; Meller, 2000). It seems that there are no arguments indicating that it would be technically unfeasible or economically inconvenient or inefficient to refine domestically the copper concentrates that Chile is currently exporting.

The first of the two main goals of this work is to estimate the avoidable quantities of fuel oil burned in transporting by sea the gangue contained in the copper concentrates exported from Chile every year. The other main goal of this study is to estimate how much more, or how much less, environmentally efficient is to smelt and refine the copper concentrates in Chile; in terms of how many more, or how many less, tons of GHG are emitted for smelting and refining 1 ton of copper concentrate in Chile, than in the more than 20 importing countries to which these concentrates are exported currently. The key factor to calculate this is the relative efficiency of the metallurgic smelting and refining technologies existing and used in the Chilean metallurgic industry compared with the average efficiency existing and used in the metallurgic industries of those other countries.

There is no additional foreseeable effects in the atmosphere if copper were to be refined in one country only or if this was done in a non-concentrated form (IPCC, 2014). In terms of potential local effects, Chile's long and diverse geography allows to locate one or more copper refining plants without effects on the population's health and eco-systemic services (ECLAC, 2009). The latter, plus the fact that a large part of copper mining and refining in Chile is located in extent desert areas with few population and without very vulnerable ecosystems nearby, indicated that most probably, the net effect of refining copper in Chile instead of in the countries that currently import Chilean copper concentrates will be a reduction in total CO2 ton-eq of GHG emissions. This is in fact corroborated by our estimations reported in the result sections below.

These results imply that a policy of refining copper concentrates domestically instead of exporting them could help Chile to achieve its international commitments to reducing GHG emissions. These commitments refer to reducing CO2 emissions per unit of gross domestic product (GDP) produced in the economy.[3] By 2013, emissions per value added in Chile were 0.92 tons of CO2-eq per million Chilean Pesos of GDP. This amount has been quite consistent through time. Emissions from copper refining for the same period were below the 0.8 tons of CO2-eq per million Chilean Pesos (López et al., 2016 and Cochilco, 2016). This means that domestically refining copper concentrates instead of exporting them worldwide would reduce total emissions per unit of value added produced in the domestic economy, which would be a change in the right direction in terms of Chile's contribution to the global efforts against global warming and climate change (OECD, 2016).

Moreover, Chile has very favorable conditions for photovoltaic power generation in areas where mining is located—Chilean mining is concentrated in regions I to IV, where solar radiation factors are around 4.5 Kcal/m^2/day, which is, for example, around 18 to 20 times the factors shown by Northern Europe. This is in addition to the interconnection, in 2017, of the two major power systems of the country (the Central Interconnected System (SIC) and the Norte Grande Interconnected System (SING)), which has reduced the price of energy and improved the ability to enter non-conventional renewable energy to the electric national system (National Electric Coordinator, 2019; Ministerio de Energía, 2015). This may imply that refining in Chile the copper concentrates currently exported by the country instead of refining them elsewhere as it is done today would prevent releasing additional carbon emissions into the global atmosphere to those we calculate in this work.

[3] For the Climate Agreement in Paris, COP21, Chile submitted its Intended Nationally Determined Contribution, in which it commits to reduce in 30% its levels of CO2 emissions per GDP unit by 2030, compared with its levels in 2007 (1.02 tCO2e/1,000,000 CLP 2011 GDP) (Government of Chile, 2015).

Here we do not include any computation of this possible additional reduction of GHG emissions released to the global atmosphere.

The next section presents the methodology employed for our estimations, and section 3 analyses the international trade of Chile's copper concentrates and describes the sources of the data used for our empirical estimations. Section 4, presents and discusses our empirical results, and in section 5 we present our conclusions and policy proposals.

2. Methodology

The methodology we use to estimate the net reduction of GHG emissions resulting from a Chile's policy of not exporting copper concentrate and replacing them by refined copper exports considers the two relevant components of the life cycle analysis (LCA) of these two copper products. The first one corresponds to the GHG emissions from the sea shipping of these products when they are exported from Chile, and the associated reduction in the total GHG emissions generated from the fuel oil burned by the freight-ships transporting for more than 15.5 million km (9.6 million miles), around 6.6 million tons of gangue incorporated in the copper concentrates currently being exported from Chile, every year. Burning this diesel oil would be avoided if instead of these cooper concentrates Chile exports only the refined copper included in those concentrates.

The second relevant component of the LCA of the two copper products under analysis corresponds to the GHG emissions generated by the metallurgic processes of these two products, and the resulting difference, i.e. the associated increase or reduction, in the GHG emissions per ton of refined copper produced from Chilean copper concentrates provoked by smelting and refining those copper concentrates in Chile instead of smelting and refining them in the countries where they are processed today after importing them from Chile. After calculating these two components, the final total net reduction in GHG emissions resulting from the relevant changes in the life cycles of these two copper products, occurring if Chile adopts the trade policy analyzed here, will be the result of adding (subtracting) to the reduction in GHG calculated in the first component the reduction (increase) in GHG emissions calculated in the second component.

The part of the life cycle analysis for refined copper involved in calculating the second component corresponds to the one beginning once the copper concentrates have been produced and still are in Chile before being exported. The previous processes these concentrates have already gone through (mine extraction, crushing, grinding, flotation, thickening, filtration, internal transport, etc.) also generate GHG emissions that are emitted to the global atmosphere. However, the amount of these GHG emission does not change with a hypothetical decision of Chile to export copper as copper concentrates instead of as refined copper (after processing the copper concentrates domestically). In other word, this part of the life cycle of copper concentrates as well as of refined copper do not change because of the trade policy.

Thus the initial product for our comparative analysis is the copper concentrate produced and still located in Chile, ready to be exported abroad or be smelted and refined in Chile; and, the final product, on the other hand, corresponds to the refined copper obtained from the copper content of the copper concentrates that has already been converted in refined cooper in Chile, and has also been exported to and it is already located in the same countries currently importing the copper concentrates exported from Chile. Fig. 1 presents a schematic illustration of that part of the life cycles for producing refined copper or copper concentrates to be exported we are referring to here (enclose by the discontinuous red line in the figure).

The methodology employed here has been designed to guarantee that reductions of the GHG emissions resulting from the Chile's hypothetical trade policy we are evaluating here are never overestimated. This guarantees that the estimations we obtained always correspond to minimum or "floor" values of the true GHG reductions that will occur in a real-world realization of the trade policy analyzed. Additionally, we do

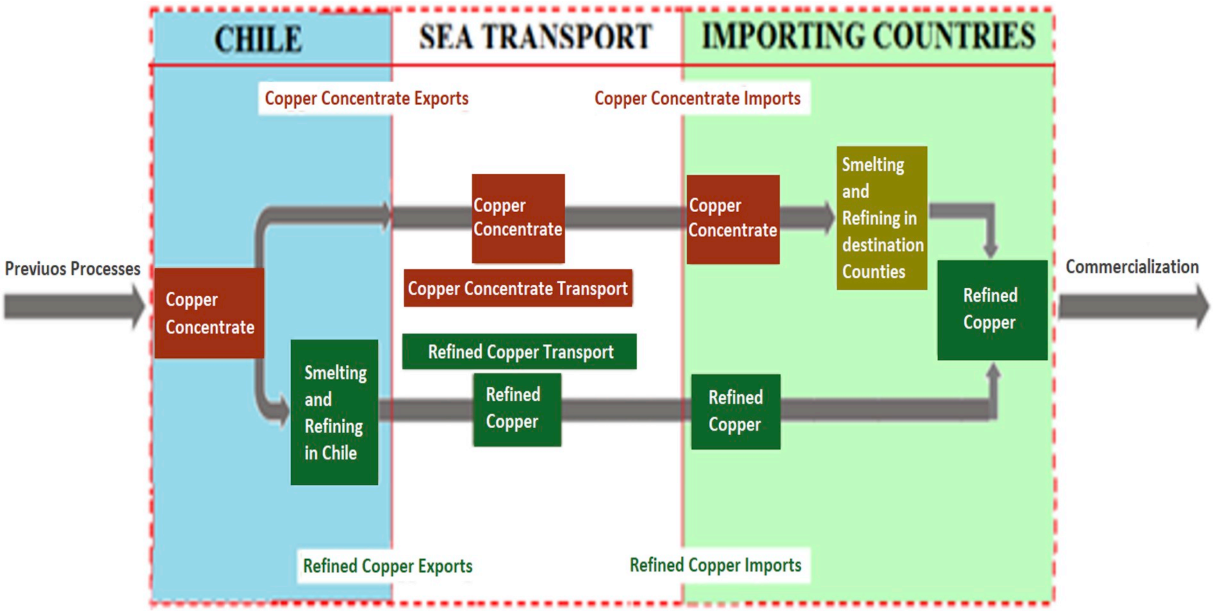

Fig. 1. Relevant components of the life cycles of Chile's exports of copper concentrate and refined copper to which changes in GHG emission are estimated.
Source: Own elaboration.

not estimate GHG emissions associated with the domestic transportation of copper concentrates from the arriving port to the corresponding refining facilities in the countries importing concentrates from Chile, because there is no data available to calculate them. I any case, it is evident that these emissions are very much lower than the emissions associated with the sea transportation of these copper concentrates, as well as with the emissions generated in their smelting and refining process.

2.1. Amount of gangue incorporated in Chile's copper concentrates

For any country "l" importing copper concentrates from Chile, the weight of the gangue content incorporated in these concentrates, E_l, can be estimated by subtracting from the total weight of these copper concentrates, measured in metric tons, the weight of the copper content in these concentrates, also measured in metric tons. Therefore, the weight of the gangue incorporated in these copper concentrates transported from Chile to the country "l" importing these concentrates is formally defined as:

$$E_l = \sum_j \sum_k \cdot E_{j,k,l} \quad [1]$$

where,

$E_{j,k,l}$= weight in metric tons of the gangue at origin port j in Chile and destination port k in the importing country l

$$E_{j,k,l} = C_{j,k,l} \cdot \left(1 - \lambda_{j,k,l}\right) \quad [2]$$

where,

$C_{j,k,l}$= the total weight of the copper concentrates shipped to port "k" in country "l" from the origin port "j" in Chile;
$\lambda_{j,k,l}$= percentage of copper in the cooper concentrate exported from origin port j in Chile to the destination port k in the importing country l

Thus, the total weight of the gangue transported during 2014 from Chile to the L countries that imported copper concentrates from Chile that year is calculated as:

$$H = \sum_{l=1}^{L} E_l \quad [3]$$

2.2. Diesel fuel burned that could be avoided by the analyzed policy

A_l is defined as the total amount of diesel oil burned due to the sea transportation of the gangue exported from Chile to country l when the freight-vessel travels through the Panama Canal. Freight-ships using the Panama Canal are of a smaller size than those that do not use the Panama Canal; and, as a result, their average oil consumption is lower per distance travelled. Thus, we calculate A_l using the following expression:

$$A_l = \frac{a}{g \cdot h} \cdot \sum_j \sum_k \left(d_{j,k,l} \cdot E_{j,k,l}\right) \quad [4]$$

where,

g = correction factor for calculating vessel's actual cargo capacity from its technically defined full capacity
a = fuel consumption of a vessel using the Panama Canal
h = correction traveling factor, for calculating actual travelled distances from origin-port to destination-port calculated without considering intermediate stops
$d_{j,k,l}$= direct nautical distance (with no intermediate stops) between Chilean origin-port j and destination-port k in importing country l

B_l is defined as the total amount of oil burned due to the transportation of gangue incorporated in the copper concentrates exported from Chile to country l, when the freight-ships do not travel through the Panama Canal:

$$B_l = \frac{b}{g \cdot h} \cdot \sum_j \sum_k \left(d_{j,k,l} \cdot E_{j,k,l}\right) \quad [5]$$

where,

b = fuel consumption of vessels that do <u>not</u> pass through the Panama Canal

Z is defined as the total oil burned from the transportation of gangue incorporated in copper concentrates exported from Chile to the rest of the world in 2014:

$$Z = \sum_{l}(A_l + B_l) \quad [6]$$

2.3. Avoidable GHG emissions from sea shipping to each importing country

Using the carbon emission factor for oil combustion provided by IPCC (2014) for the different types of ships that transport copper concentrates from Chile, it is possible to obtain an expression for the GHG emissions generated (expressed in CO2-eq tons) by importing country "l" from the gangue transported through the Panama Canal $-C_l-$ plus the gangue transported through routes different to the Panama Canal $-D_l$:

$$C_l = f \cdot A_l \quad [7]$$

$$D_l = f \cdot B_l \quad [8]$$

where,

f = factor of diesel fuel-related carbon emissions

2.4. GHG emissions from smelting and refining copper concentrates in Chile and in those countries importing them from Chile

Using equation [2], in equation [9] we obtain an expression formally defining the amount of copper content that arrives to the importing country l, R_l, incorporated in the copper concentrates imported from Chile:

$$R_l = \sum_{j}\sum_{k} C_{j,k,l} \cdot L_{j,k,l} \quad [9]$$

To estimate the GHG emissions generated from smelting and refining the copper concentrates we use a factor of emission specific to each country, depending on the smelting and refining technology each country has. Then, there are 2 basic cases for which it is necessary to calculate smelting and refining GHG emissions: 1. if the concentrates are refined in Chile; and, 2. if the concentrates are refined in any of the countries importing copper concentrates from Chile. Therefore, we define as U_l to the amount of GHG emissions generated if copper concentrates imported from Chile by county "l" are smelted and refined in country "l" and, as T to the total amount of GHG emissions generated if all copper concentrates exported from Chile are smelted and refined in Chile; and, in equations [10] and [11] we show the expressions to calculate them:

$$U_l = R_l \cdot S_l \quad [10]$$

where,

S_l = country l's GHG emission factor from smelting and refining copper concentrates

$$T = S_{ch} \cdot \sum_{l=1}^{L} R_l \quad [11]$$

where,

S_{ch} = Chile's GHG emission factor from smelting and refining copper concentrates.

2.5. Avoidable net total GHG emissions from Chile's policy of refining copper concentrates domestically and exporting only refined copper

Using equations [7] and [8], it is possible to calculate the total amount avoidable GHG emissions resulting from not transporting the gangue incorporated in copper concentrates from Chile to the countries importing these concentrates.

$$W = \sum_{l=1}^{L} (C_l + D_l) \quad [12]$$

As explained before, to obtaining the final total avoidable carbon emissions is it necessary to estimate the change in GHG emissions provoked because the smelting and refining of copper concentrates is switched to Chile from the countries importing these concentrates from Chile. This change can be positive or negative (and increase or a decrease in the GHG generated), depending on the relative size of S_{ch} and S_l. In fact, and as it follows from equations [10] and [11], if $S_{ch} < S_{chl}$, refining copper concentrates in Chile will generate less GHG emissions that refining them in the countries that currently import them from Chile. The opposite will occur if $S_{ch} > S_{chl}$.

More formally, defining as V the total GHG emissions generated from smelting and refining Chile's copper concentrates in the importing destination countries, then the following expression allows to calculate it:

$$V = \sum_{l=1}^{L} U_l \quad [13]$$

Finally, it is possible to define Y as the total amount of avoidable GHG emissions from smelting and refining copper concentrates in Chile instead of abroad; and, therefore, using equations [11], [12] and [13] the expression for Y is:

$$Y = W + (V - T) \quad [14]$$

3. Trade of Chile's cooper concentrates and data sources

For doing our most relevant empirical estimations we use data for 2014, which is the most recent year for which there is official data on copper concentrate exports with the detailed information on every exported shipment required for our calculations. The database of the Central Bank of Chile (2015) shows that, in 2014, 919 shipments of exported copper concentrates were sent abroad from Chile and provides, for each of them, the following information relevant to our study: 1. the exporting company or entity; 2. the total gross amount of the copper concentrate (including moisture); 3. the percentage of copper content in the concentrates (copper mass over gross amount of concentrate mass); 4. origin port in Chile; 5. importing country; and, 6. destination port in the importing country.

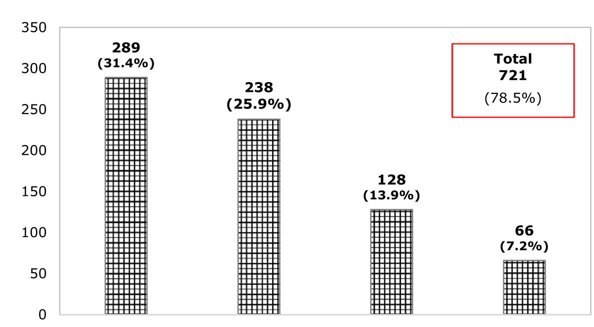

Fig. 2. Chile: Number of copper concentrate shipments exported to the 4 main importing countries; 2014 (number of landings).
Source: Own elaboration, using information from the Central Bank of Chile (2015).

Fig. 2 shows that China, Japan, India and South Korea received the largest numbers of copper concentrate shipments imported from Chile. They jointly received 721 shipments, or 78.5%, of the total shipments exported from Chile in 2014. Most of these shipments were sent abroad from only 4 Chilean ports that dispatched 680 shipments altogether, or 74% of all shipments: Caleta Coloso (239 shipments with 26%); Ventanas (196 shipments with 21.3%); Patache (135 shipments with 14.7%); and, Los Vilos (110 shipments and 12%).

Fig. 3 shows that the same 4 importing countries –China, Japan, India and South Korea– received the largest amounts of copper concentrate exported from Chile, 7,700,889 metric tons altogether, representing 82% of the total amount of metric tons of copper concentrates exported from Chile in 2014.

More details regarding the shipments of Chile's copper concentrate to the destination countries in 2014 are presented below in Appendices A, B and C.

3.1. Copper content of copper concentrates

Using data on the shipments of copper concentrates exported in 2014, and the copper content reported by the National Customs Service for each shipment, we estimated that the average copper content of the copper concentrates exported from Chile that year was 30%. Also, 13 of the 18 companies exporting copper concentrates that year, or 72.2% of all of them, exhibited a copper content of their shipments between 25% and 30%.

3.2. Origin-destination ports matrix of Chile's exported copper concentrates in 2014

We identified a total of 97 different origin-destination maritime routes by which the shipments of exported copper concentrates were sent from Chile to the rest of world in 2014. For each one of these routes, we calculated the direct nautical distance involved, using the computer tool "Distances and Times" (Sea Rates, 2017). We also determined whether each of these routes included or not crossing through the Panama Canal.

Appendix D below shows in detail the 97 routes, reporting their distances in kilometers, the amount of gangue transported through the route, and whether the route crossed the Panama Canal or not. It is worth noting that these routes were analyzed as if they were direct trips from the origin Chilean port to the final destination port, which is not actually the case, as vessels, more often than not, do make stopovers in their routes. This is analyzed with more detail in Section 3.4 below.

Table 2 shows the routes using and not using Panama Canal., their average distances, the total amount of gangue transported for each route and the percentage of gangue content.

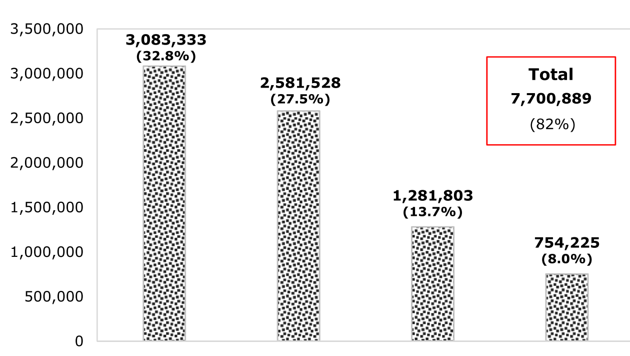

Fig. 3. Chile: Amount of copper concentrate exported from Chile to the 4 main importing countries; 2014 (tons).
Source: Own elaboration, using information from the Central Bank of Chile (2015).

Table 2
Chile: Distance travelled, total amount of gangue transported and % of total. copper concentrates transported, by type of shipping route; 2014.

ITEM	ROUTES THROUGH THE PANAMA CANAL	ROUTES NOT CROSSING THE PANAMA CANAL
AVERAGE NAUTICAL DISTANCE	14,271 km	15,940 km
TRANSPORTED GANGUE	768,601 tons	5,807,982 tons
% OF TOTAL COPPER CONCENTRATE TRANSPORTED	12%	88%

Source: Own elaboration, using information from the Central Bank of Chile (2015) and Sea Rates (2017).

3.3. Freight-ships transporting copper concentrates from Chile

As of 2014, ships with gross tonnage over 52,000 tons were not allowed to use the Panama Canal route; therefore, we assumed here that copper concentrates exported from Chile through this route were transported on ships of the "Panamax" type. On the other hand, the maritime routes that do not cross the Panama Canal do not imply capacity limitations on ship tonnage. With the purpose of avoiding any possible overestimation when we estimate the reduction in GHG emissions generated by Chile's hypothetical trade policy under analysis, we assume that the representative ship for the routes not crossing the Panama Canal corresponds to a large, efficient fright-vessel of the "MSC Oscar" type from the Mediterranean Shipping Company, with a gross tonnage of 193,000 tons.

Table 3 shows the relevant features of both types of freight-ships used to perform the calculations of this study, obtained from Alphaliner (2011) and Access (2014) for the case of the "Panamax" vessels, and from ABB (2015) and MSC (2017) for the "MSC Oscar" ships.

3.4. Technical correction factors

Fuel consumption rates of freight-ships may be affected by several conditions, especially in long trips, causing that their actual fuel consumption rates are lower than their potential (most efficient) fuel consumption rates. Therefore, for our fuel consumption estimations we have followed Access (2014) and considered that the average actual fuel consumption rates of the freight-ships transporting copper concentrates exported from Chile are 80% of their potential most efficient rates. As a result, for our calculations the average fuel consumption rate used for the ships of the "Panamax" type is 114 L per km travelled, and for ships of the "MSC Oscar" type is 336 L per km travelled.

The technical specifications of the gross tonnage of the freight-ships shown in Table 5 must be corrected to obtain the actual cargo capacity of each type of vessel. Hence, following Trozzi (1999) we employ here a correction factor of 55% to calculate the actual cargo capacity of each type of freight-ship.

Additionally, to calculate the travel distance involved in every shipment of copper concentrates, we have estimated the nautical

Table 3
Key technical characteristics of the freight-ships transporting copper concentrates exported from Chile.

TECHNICAL CHARACTERISTIC	TYPE OF FREIGHT SHIP	
	MSC Oscar	Panamax
GROSS TONNAGE	193,000 tons	52,000 tons
FUEL TYPE	Diesel	Diesel
FUEL CONSUPTION	>280 L per km	>95 L per km

Source: Own elaboration, with information from Alphaliner (2011), Access (2014), ABB (2015) and MSC (2017).

Table 4
GHG emission generation factors of the metallurgic technologies to smelt and refine copper concentrates in countries importing. copper concentrates from Chile.

COUNTRY	GHG EMISSION GENERATION FACTOR	SOURCE
	(ton CO2-eq /ton Cu)[a]	
CHILE	0.44	Cochilco (2018)
CHINA	0.65	ESG (2017)
JAPAN	0.75	JX Nippon Mining and Corporation, 2017
INDIA	1.09	Hindalco (2017)
SOUTH KOREA	0.71	USGS (2017)
BRAZIL	0.54	Paranapanema (2018)
SPAIN	0.41	Atlantic Copper (2017)
BULGARIA	0.46	Dundee (2018)
GERMANY	0.52	Aurubis (2018)
FINLAND	0.69	Boliden (2017)
SWEDEN	0.67	Boliden (2017)

[a] Average value for 2016–2017.
Source: Own elaboration.

Table 5
Structure of the 4 scenarios used for the sensitivity analysis of the estimations of the net total reduction in GHG emissions resulting from refining Chilean copper concentrates domestically instead of exporting. them as copper concentrates.

SENSITIVITY ANALYSIS SCENARIO	SHIPPING DISTANCE CORRECTING FACTOR		FUEL USE FACTOR	
	Panamax Ship	MSC Oscar Ship	Panamax Ship	MSC Oscar Ship
	(%)		(diesel fuel liters /km)	
A	60	70	95	280
B	70	80	95	280
C	60	70	114	336
D	70	80	114	336

Source: Own elaboration.

distance travelled as in a direct trip from the corresponding port in Chile to the final destination port. However, freight-ships very often do not travel directly from the port of origin to the final port but they make intermediate stops, which increases the actual travel distance, especially for vessels passing through the Panama Canal. To incorporate this in our estimations, we have used a correcting factor expressed as the ratio of the estimated direct nautical distance over the actual travelled distance. As proposed by Enertrans (2008), Trozzi (1999) and Access (2014), for those ships passing through the Panama Canal we have used a ratio of 0.7 (and a ratio of 0.6 to estimate and alternative scenario), and for the ships not using the Panama Canal we used a ratio of 0.8 (and a ratio of 0.7 to estimate and alternative scenario).

Finally, we calculate the amounts of the different greenhouse gases (CO2, methane, nitrous oxide, ozone, etc.) emitted to the global atmosphere from the oil burned by the freight-ships transporting the copper concentrates exported from Chile in terms of their equivalent tons of CO2. To perform the involved transformation, we use the converting factor calculated by the Intergovernmental Panel on Climate Change, which is 2.8 tons of CO2-eq per cubic meter of oil burned (IPCC, 2014).

3.5. GHG emissions from smelting and refining copper concentrates

As explained before, to calculate the total amount of GHG emissions avoided by smelting and refining the copper concentrates in Chile instead of exporting them, it is also necessary, in addition to calculate the emissions avoided from the ship transportation of the gangue incorporated in the copper concentrates, to calculate the difference in total GHG generated by the smelting and refining processes when they are done in Chile compared to when they are done in those countries currently importing those concentrates from Chile.

If smelting and refining these concentrates in Chile generates less GHG than doing it abroad, then the calculated difference will be an additional contribution to the GHG reduction generated from avoiding the sea transportation of the gangue incorporated in the copper concentrates. On the contrary, if smelting and refining the concentrates in Chile generates more GHG emission than smelting and refining them abroad, the calculated difference will reduce the net total reduction in GHG emissions implied by Chile's decision of exporting refined copper instead of copper concentrates.

To do these estimations, we analyzed the group of 10 countries that jointly imported more than the 98% of the copper concentrates exported by Chile in 2014. We gathered detailed information on the GHG emissions generated by the copper smelting and refining technologies of these countries and Chile. In Table 6, we present the information obtained for each of these countries' metallurgic technologies, in terms of the direct GHG tons of CO2-eq of GHG they emit per ton of refined copper. As shown in the table, the average pollution rate for the technologies of the 11 countries in the table is 0.63 tons of CO2-eq per ton of refined copper; and Spain and Chile exhibit the less polluting technologies of the group, with 0.41 and 0.44 tons of CO2-eq per ton of refined copper, respectively, and are the only two countries in the group with best environmental technologies, i.e. with GHG emission generator factors between one and less than two standard deviations below the average factor. Moreover, Brazil, Bulgaria and Germany are, in the group of countries exhibiting the second less polluting technologies, i.e. with GHG emission generator factors up to less than one standard deviation below the average factor; China, Japan, South Korea, Finland and Sweden are in the group of countries whose technologies are less than one standard deviation more polluting than the average; and India is the only country of the group with a technology that is more polluting than the latter group, with a pollution rate of 1.09 tons of CO2-eq per ton of refined copper. For the estimations involving the other 12 countries importing and refining the remaining 2% of Chile's exported copper concentrates we used the average environmental efficiency rate of 0.63 tons of CO2-eq per ton of refined copper (which includes Chile's environmental efficiency rate).[4]

Table 6
Avoided GHG emissions and not burned diesel fuel in four scenarios for sensitivity analysis.

SENSITIVITY ANALYSIS SCENARIO	GHG EMISSIONS AVOIDED	DIESEL FUEL BURNING AVOIDED
	(ton of CO2-eq)	(ton)
A	1,682,946	601,052
B	1,445,551	515,911
C	2,017,783	721,262
D	1,903,388	619,093
AVERAGE	1,762,417	614,330

Source: Own estimations.

[4] The purpose of including Chile's environmental efficiency in this average is, once again, to eliminate any risk of overestimating the reduction in GHG emissions resulting from the Chile's hypothetical trade policy under analysis.

4. Results

4.1. GHG emissions avoided from copper concentrate sea shipping

4.1.1. Sensitivity analysis scenarios for the estimations

As noted in the previous section, two key parameters are involved in the estimation of the amount of the GHG emissions that could be reduced if copper concentrates are refined in Chile instead of being exported as such. The first of them is the correcting factor used to estimate the actual distance travelled by the ships transporting each shipment of copper concentrate exported from Chile, starting from an estimate of this distance from the origin Chilean port to the final destination port without considering the usual intermediate stopovers made by the ships. The second of these key parameters corresponds to the oil consumption rate per kilometer travelled by the two kinds of freight-ships involved. Therefore, in order to perform sensitivity an analysis in our estimations we use two different values for each of these two key parameters. Thus, we calculate 4 different scenarios of the net total reduction of GHG emissions resulting from refining Chilean copper concentrates domestically and exporting their copper content as refined copper afterwards. Table 5 shows the combination of the values of the 2 key parameters used for each one of the 4 sensitivity scenarios estimated.

4.1.2. GHG emissions avoided from gangue sea shipments

For each of the 4 scenarios described in Table 5 we calculate the CO2-eq tons of all GHG emissions generated by the sea transport of the gangue included in the copper concentrates exported from Chile in 2014. We estimate the amount of these emissions for the 919 shipments sent to every destination port in each one of the 22 countries that imported Chilean copper concentrates that year. Evidently, the amounts of these emissions corresponds to the GHG emission that would had been avoided if, in 2014, Chile would had exported refined copper instead of copper concentrates, avoiding in this way the sea shipping of the gangue contained in the copper concentrates exported. Table 6 shows the estimations obtained for each one of our four sensitivity scenarios, presenting the amounts of total GHG emissions that would have been avoided and the amounts of diesel fuel that would have not been burned.

Column 2, in turn, shows that the amounts of GHG emissions generated by this burned fuel were, for the four scenarios estimated, between 1,445,551 and 2,017,783 tons of CO2 equivalent. Column 3 of Table 6 shows that the total volume of diesel oil burned to transport the gangue content included in the copper concentrates exported from Chile was, in 2014, between 515,911 and 721,262 tons, which could be avoided. The estimations for each one of 22 countries that imported those Chilean copper concentrates in 2014 are presented in Appendix E.

4.2. GHG emissions avoided if the metallurgic processes to smelting and refining Chile's copper concentrates were carried out in Chile instead of abroad

To estimate the final total net GHG emissions involved in the hypothetical Chile's decision of exporting refined copper instead of copper concentrates, it is necessary to add to (to subtract from) the figures presented in Table 6, the reduction (the increase) in GHG emissions resulting from the metallurgic processes of smelting and refining the copper concentrates in Chile instead of in the 22 countries importing the concentrates from Chile. Our estimations show that the smelting and refining of copper concentrates in Chile instead of in the importing countries in fact provokes a net reduction in GHG emissions. The reason of this, as it is explained by the GHG emission factors of the different countries reported in Table 4 above, is that the environmental efficiency of Chile's copper smelting and refining processes is higher than the efficiencies exhibit by the 9 of the 10 countries importing 98% of Chile's copper concentrates and it is also 30.2% higher than the average for those 10 efficiency. This is the underlying explanation of our estimations indicating that if all copper concentrates exported by Chile in 2014 would had been smelted and refined in Chile the total amount of GHG emission generated by the metallurgic processes involved would had been 1,235,872 tons of CO2-eq, which means 781,496 tons less than the CO2-eq tons of GHG that were produced by those 22 countries −2,017,368 tons− when they smelted and processed the copper concentrates they imported from Chile that year.

Appendix F below shows the GGH emissions produced by each one of the 22 countries that imported copper concentrates from Chile, in 2014.

4.3. Total GHG emissions to the global atmosphere avoided from refining copper concentrates in Chile and exporting their copper content as refined copper

When we add both GHG emission reductions we have estimated, resulting from the hypothetical trade policy of Chile under analysis, we obtain a net total reduction of GHG emissions liberated to the global atmosphere of between 2,227,047 and 2,799,279 tons of CO2-eq. Indeed, as shown in column 2 of Table 7, we have obtained an estimate for each one of the 4 scenarios we have developed here for the sensitivity analysis of our calculations, and the average reduction estimated for the 4 scenarios is 2,543,913 tons. Moreover, to illustrate the relative magnitude of these estimates, they are presented in column 3 of the table as percentages of Chile's total annual GHG emissions, for the year 2014 (105 million tons of CO2-eq (MMA, 2018)). The figures shown indicate that the avoided GHG emissions were equivalent to a minimum of 2.2% (scenario B) to a maximum of 2.8% (scenario C) of Chile's total annual GHG emissions of 2014, and that the average for the 4 sensitivity scenarios was equivalent to 2.5%. Additionally, as it is shown in column 4 of the table, the avoided GHG emission estimated were equivalent to a minimum of 4.9% (scenario B) to a maximum of 6.1% (scenario C) of Chile's net annual GHG (48.5 million tons of CO2-eq, MMA (2018)), and that, in this case, the average for the 4 sensitivity scenarios was equivalent to 5.6%.

Thanks to a suggestion of an anonymous referee of this journal we significantly improved our estimates of the embodied emissions generated in the whole production process of Chile's copper concentrate and refined copper exports reported here, by extending them through a more encompassing life cycle analysis. To do that, we used some of our findings from a parallel ongoing research that attempts to estimate the carbon footprint of the Chilean economy, and uses an input-output methodology (see López et al., 2016). In Table 8, we use again some of these parallel findings in order to better illustrate the relative magnitude of our estimates of Chile's avoided GHG emissions to the

Table 7
Chile: GHG emissions to the global atmosphere avoided by a hypothetical policy to completely replace its 2014 copper concentrate exports by refined copper exports, expressed in tons of CO2-eq and as percentages of Chile's annual Total and Net. GHG emissions; estimations for four scenarios of sensitivity analysis.

SENSITIVITY ANALYSIS SCENARIO	AVOIDED GHG EMISSIONS TO THE GLOBAL ATMOSPHERE		
	ABSOLUTE VALUE	AS PERCENTAGE OF CHILE'S ANNUAL	
		TOTAL GHG EMISSIONS	NET GHG EMISSIONS
	(ton of CO2-eq)	(%)	
A	2,464,442	2.4	5.4
B	2,227,047	2.2	4.9
C	2,799,279	2.8	6.1
D	2,684,884	2.6	5.9
AVERAGE	2,543,913	2.5	5.6

Source: Own elaboration with data from MMA (2018) and own estimates.

Table 8
Chile: GHG emissions to the global atmosphere avoided by a hypothetical policy to completely replace its 2014 copper concentrate exports by refined copper exports, expressed as percentages of Chile's mining sector GHG emissions; estimations for four scenarios of sensitivity analysis.

SENSITIVITY ANALYSIS SCENARIO	GHG EMISSIONS AVOIDED AS PERCENTAGE OF CHILE MINING SECTOR'S GHG EMISSIONS			
	DIRECT	INDIRECT EMISSIONS		
	EMISSIONS	ELECTRICITY & GAS	TRANSPORT	MANUFATURES
	(%)	(%)		
A	44.8	30.8	200.8	281.1
B	40.5	27.8	181.5	254.1
C	50.9	35.0	228.1	319.3
D	48.8	33.5	218.8	306.23
AVERAGE	46.3	31.8	207.3	290.2

Source: Own elaboration with data from MMA (2018), López et al. (2016), and own estimates.

global atmosphere reported in Table 7. In fact, column 2 of Table 8 presents our estimates of the GHG emissions to the global atmosphere avoided expressed now, as percentages of the direct (as opposed to the indirect) GHG emissions generated by the mining sector of Chile in the year 2014 (5.5 million tons of CO2-eq, Cochilco (2018)). These percentages indicate that the avoided GHG emissions estimated here were between a minimum of 40.5% (for scenario B) and 50.9% (for scenario C) of Chile's mining sector direct annual GHG emissions; and, that they represented 46.3% of the average GHG emissions generated by the 4 scenarios of the sensitivity analysis performed here.

On the other hand, in columns 3, 4 and 5 of Table 8, we show our estimates of the avoided GHG emissions expressed in this case, as percentages of the indirect GHG emissions generated by the mining sector of Chile in the year 2014 (17.2 million tons of CO2-eq, based in López et al., 2016). These estimated percentages are separated in the three sub-sectoral components employed in the input-output analysis of Chile's national account system: electricity and gas; transport; and, manufactures. As the relative sizes of the three sub-sectors are quite different, the estimated percentages are also quite different. In fact, considering the averages for the 4 sensitivity scenarios employed here, these estimated percentages go from the lowest, of 31.8%, for the GHG emissions generated by the sub-sector of electricity and gas; to the intermediate of 207%, for the GHG emissions generated by the transport sub-sector; to the highest, of 290.2%, for the GHG emissions generated by the sub-sector of manufactures. Nevertheless, in spite of their ample range, these percentage proportions clearly indicate that the contribution that Chile would made by completely replacing its current exports of copper concentrates by refined copper exports would be significant from several points of view, and with relevance not only for its mining sector but also from a national perspective.

5. Conclusions and policy proposals

Of all the GHG emissions that Chile emitted to the global atmosphere in 2014, 2,227,047 to 2,799,279 tons were generated from two sources related to its copper exports. First, by the diesel oil burned to transport Chile's copper concentrates exported to the 22 countries who imported them. Second, by the environmentally dirtier processes used afterwards in those 22 countries to smelt and refine those copper concentrates, compare with the same metallurgic processes used in Chile. Obviously, these large amounts of GHG emissions are not insignificant. For example, they represented around 50% of all the direct GHG emissions released that year by the entire copper mining sector of Chile, the largest copper producing country, who produces 30% of all the copper annually produced in the world. On the other hand, they were also equivalent to 5.6% of the amount of GHG emissions that Chile would have needed to mitigate that year to make its economy fully carbon neutral, and to 2.5% of the total amount of GHG emitted by Chile that year. Therefore, if these more than 2,500,000 tons of CO2-eq GHG would had been mitigated instead of released to the atmosphere, they would had made a valuable contribution to the world's efforts to reduce climate change and global warming that year. Moreover, Chile could make a contribution like this, every year in the future, by adopting a trade policy of not exporting copper concentrates any longer, replacing them by refined copper exports.

Chile committed to the 2015 Paris Agreement a 30% reduction of its CO2 emissions per unit of GDP by 2030, relative to its levels in 2007. This involves going from 1.02 to 0.71 tons of CO2-eq per million Chilean Pesos of GDP in 23 years (Government of Chile, 2015). Given the importance of the mining sector in Chile's total GDP, these figures imply that the sector should play a significant role in reducing the country's GHG emission per million Chilean pesos of GDP. One way of doing this contribution would by refining all its copper domestically instead of continuing with exporting copper concentrates. The latter results from the fact that the GHG intensity per million Chilean pesos of GDP of the domestic copper refining processes is 0.8 CO2-eq tons of GHG per million Chilean pesos of GDP, which is less than the intensity of the entire mining sector of 0.92 (as estimated by López et al., 2016).

The International Maritime Organization (IMO) of the United Nations estimated that, in 2012, the GHG emissions from international shipping accounted for 2.2% of anthropogenic CO2 emissions and that, by 2020, such emissions will grow between 50% and 250% (IMO, 2015). To join the world effort to reduce climate change and global warming, IMO is committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century (MEPC, 2018).

To pursue these objectives, the IMO defined its Initial Strategy, one of whose levels of ambitions is to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050, compared to 2008. Moreover, IMO is committed to pursue efforts towards phasing out international shipping GHG emissions as a point on a pathway of CO2 emissions reduction consistent with the Paris Agreement temperature goals (MEPC, 2018). There is no doubt then, that Chile could make a substantive contribution in line with these IMO's objectives by reducing the GHG emission generated from the sea shipping of its annual exports of copper concentrates, substituting them by refined copper exports.

On the other hand, the growing evidence indicating that the international efforts committed in the 2015 Paris Agreement would not be sufficient to slowing down global warming with the required speed pushed the IPCC to launch, at the end of 2018, its Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways. In this report the IPCC urges the global community to strengthen current efforts to attaining pathways to limit global warming to 1.5 °C instead of 2 °C, because, with high confidence, the pathways reflecting the ambitions of the Paris Agreement would not limit global warming to 1.5 °C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (IPCC, 2018). Moreover, at the UN Climate Action Summit, held in New York on last September 21–23, the UN Secretary-General, António Guterres, asked to all world leaders to propose concrete, realistic plans to enhance their nationally determined contributions by 2020, in line with reducing greenhouse gas emissions by 45% over the next decade, and to net zero emissions by 2050.

To meet these tough challenges, the world maritime transport sector can make a significant contribution, because 80% of the world's merchandise transport is made by sea. This is why, in the Climate Action Summit of last September, the Secretary General of the International Maritime Organization, Kitack Lim, committed this UN organization's efforts to attempt to reduce in 40% the CO2 intensity of sea transport by 2030, relative to 2008, and to reach 70% towards 2050. To honor these commitments, it would be convenient that the IMO plays a more active role to generate incentives to motivate all countries to implement initiatives for reducing the GHG generated by their international shipping activities.

A proposal to attain this would be to determine that the amounts of GHG emissions mitigated by a country as a result of reducing the sea shipping of its exports can be accounted as part of its future national determined contribution (NDC). An internationally agreed policy like this would create large incentives for all countries to reduce the GHG emissions generated by the sea shipping of their exports; which, in the case of the mining sector of Chile studied here, implies eliminating its exports of copper concentrates. The latter would reduce the GHG intensity of Chile's mining sector in more than the 30% reduction in the GHG intensity per million Chilean Pesos of GDP already committed by the country to the Paris Agreement. Of course, this would be beneficial to Chile but, more relevant than that, this recognition of the GHG emissions reductions from sea shipping would align the incentive of all countries with the world efforts to reduce global GHG emissions.

On November 29, 2019, the Assembly of the IOM reelected Chile as a member of the IMO's Council, the executive organ responsible for supervising the work of the Organization. This occurred only three days before the COP 25 to the United Nations Framework Convention on Climate Change (UNFCCC) will convene in Madrid, Spain, under the Presidency of Chile, and in which the safeguard of global oceans as well as the reductions in GHG emission to the atmosphere will be relevant issues. Both of these facts represent opportunities for Chile to promote in the international arena the necessary changes to increase the current existing incentives for countries to reduce GHG emissions from the sea transportation of their exported merchandises by obtaining their recognition as part of their NDCs.

CRediT authorship contribution statement

Gino Sturla-Zerene: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing. **Eugenio Figueroa B:** Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision. **Massimiliano Sturla:** Data curation, Visualization.

Appendix A

Chile: Amount of exported gangue and equivalent refined copper by shipping port; 2014.

PORT OF ORIGIN	GANGUE	EQUIVALENT REFINED COPPER
	(ton)	
ANTOFAGASTA	125,406	54,651
ARICA	3,614	1,426
CALDERA	373,409	154,552
CALETA COLOSO	1,726,577	802,787
CHANARAL/BARQUITO	28,334	12,223
COQUIMBO	323,605	118,428
LOS VILOS	795,854	441,228
MICHILLA	600,274	192,742
PATACHE	1,088,245	432,818
PUERTO ANGAMOS	29,745	15,452
SAN ANTONIO	3,599	1,394
VALPARAISO	3,844	1,278
VENTANAS	1,474,077	579,884
TOTAL	**6,576,584**	**2,808,861**

Source: Own elaboration.

Appendix B

Chile: Copper Concentrate exported, and equivalent refined copper content, by exporter; 2014.

EXPORTER	COPPER CONCENTRATE	EQUIVALENT REFINED COPPER CONTENT
	(ton)	(%)
ANGLO AMERICAN NORTE S.A.	545,387	28.3%
ANGLO AMERICAN SUR S.A.	1,164,460	28.1%
CIA.CONT. MINERA CANDELARIA	527,961	29.3%
CIA.MIN.DONA INES COLLAHUASI S	975,676	28.5%
CIA.MINERA TECK CARMEN DE ANDA	276,049	27.0%
CODELCO CHILE	1,102,253	28.9%
EMPRESA NACIONAL DE MINERÍA	15,744	36.1%
GLENCORE CHILE S.A.	57,751	27.6%
MINERA CENTINELA	43,542	25.9%
MINERA CERRO DOMINADOR S.A.	1,475	22.2%
MINERA ESCONDIDA LTDA	2,529,363	31.7%
MINERA ESPERANZA	749,473	24.2%
MINERA LAS CENIZAS S.A.	10,053	26.1%
MINERA LOS PELAMBRES	1,237,082	35.7%
SCM MINERA LUMINA COPPER CHILE	57,661	26.0%
SIERRA GORDA SCM	14,773	28.6%
SOC. CONTRACTUAL MINERA ATACAMA	5,857	27.7%
TRAFIGURA CHILE LTDA	70,883	25.9%
TOTAL	**9,385,444**	**30.0%**

Source: Own elaboration.

Appendix C

Chile: Gangue and equivalent refined copper, by destination country; 2014.

DESTINATION COUNTRY	GANGUE	EQUIVALENT REFINED COPPER
	(ton)	
GERMANY	163,055	62,443
BRAZIL	324,490	137,271
BULGARIA	168,454	71,322
CANADA	653	203
CHINA	2,166,088	917,245
SOUTH KOREA	528,609	225,616
SPAIN	319,326	130,299
PHILIPPINES	14,538	7,466
FINLAND	66,659	25,217
GEORGIA	722	372
NETHERLANDS	3,787	1,671
HONG KONG	2,874	1,481
INDIA	892,103	389,699
JAPAN	1,798,180	783,348
MALAYSIA	844	380
MEXICO	7,818	3,834
NAMIBIA	29,558	14,185
PERU	8,493	3,506
SWEDEN	45,945	17,821
TAIWAN	31,494	13,990
THAILAND	2,147	1,106
VIETNAM	747	385
TOTAL	**6,576,584**	**2,808,861**

Source: Own elaboration.

Appendix D

Chile: Domestic and destination ports, gangue transported, maritime route and travelled distance of copper concentrated shipments; 2014.

PORT OF ORIGIN	PORT OF DESTINATION	GANGUE CONTENT	NAUTICAL DISTANCE	MARITIME ROUTE
		(ton)	(km)	Panama Canal = 1 No Panama Canal =0
ANTOFAGASTA	CALLAO	600	1,639	0

(continued on next page)

(*continued*)

PORT OF ORIGIN	PORT OF DESTINATION	GANGUE CONTENT	NAUTICAL DISTANCE	MARITIME ROUTE
ANTOFAGASTA	HUELVA	7,559	12,150	1
ANTOFAGASTA	KAOHSIUNG	4,316	19,008	0
ANTOFAGASTA	KEELUNG	5,933	18,887	0
ANTOFAGASTA	MANZANILLO	3,064	6,221	0
ANTOFAGASTA	OTHER PARTS OF INDIA	30,248	19,174	0
ANTOFAGASTA	OTHER PARTS OF PANAMA	1,223	4,108	0
ANTOFAGASTA	OTHER PARTS OF CHINA	20,094	18,681	0
ANTOFAGASTA	OTHER PARTS OF NAMIBIA	22,243	11,407	0
ANTOFAGASTA	OTHER PARTS OF NETHERLANDS	3,787	13,072	1
ANTOFAGASTA	OTHER PARTS OF JAPAN	3,670	16,932	0
ANTOFAGASTA	OTHER PARTS OF SWEDEN	9,450	14,502	1
ANTOFAGASTA	PORI	9,431	14,689	1
ANTOFAGASTA	VARNA	3,787	15,852	1
ARICA	OTHER PARTS OF CHINA	3,614	18,318	0
CALDERA	HUELVA	117,580	12,342	1
CALDERA	OTHER PARTS OF INDIA	40,688	18,828	0
CALDERA	OTHER PARTS OF BRAZIL	7,350	7,680	0
CALDERA	OTHER PARTS OF CHINA	66,065	14,926	0
CALDERA	OTHER PARTS OF KOREA	15,428	18,224	0
CALDERA	OTHER PARTS OF JAPAN	113,929	17,121	0
CALDERA	OTHER PARTS OF SWEDEN	12,370	14,694	1
CALETA COLOSO	OTHER PARTS OF INDIA	376,853	19,161	0
CALETA COLOSO	OTHER PARTS OF BRAZIL	106,376	8,014	0
CALETA COLOSO	OTHER PARTS OF CHINA	643,367	18,676	0
CALETA COLOSO	OTHER PARTS OF KOREA	208,607	18,027	0
CALETA COLOSO	OTHER PARTS OF JAPAN	383,552	16,927	0
CALETA COLOSO	OTHER PARTS OF TAIWAN	7,821	18,882	0
CHANARAL/BARQUITO	KAOHSIUNG	1,514	18,899	0
CHANARAL/BARQUITO	OTHER PARTS OF INDIA	11,919	18,883	0
CHANARAL/BARQUITO	OTHER PARTS OF CHINA	7,704	18,775	0
CHANARAL/BARQUITO	OTHER PARTS OF JAPAN	4,235	17,043	0
CHANARAL/BARQUITO	VARNA	2,962	15,978	1
COQUIMBO	ILO	4,215	1,450	0
COQUIMBO	OTHER PARTS OF INDIA	34,420	18,483	0
COQUIMBO	OTHER PARTS OF BULGARIA	35,756	16,312	1
COQUIMBO	OTHER PARTS OF PANAMA	3,530	4,607	0
COQUIMBO	OTHER PARTS OF GERMANY	83,642	14,037	1
COQUIMBO	OTHER PARTS OF BRAZIL	16,430	7,336	0
COQUIMBO	OTHER PARTS OF CHINA	29,090	18,794	0
COQUIMBO	OTHER PARTS OF KOREA	8,478	18,230	0
COQUIMBO	OTHER PARTS OF JAPAN	42,669	17,171	0
COQUIMBO	OTHER PARTS OF SWEDEN	15,975	15,001	1
COQUIMBO	PORI	49,400	15,188	1
LOS VILOS	HUELVA	27,811	12,649	1
LOS VILOS	OTHER PARTS OF INDIA	40,877	18,483	0
LOS VILOS	OTHER PARTS OF BULGARIA	41,432	16,312	1
LOS VILOS	OTHER PARTS OF GERMANY	14,301	14,037	1
LOS VILOS	OTHER PARTS OF BRAZIL	21,221	7,336	0
LOS VILOS	OTHER PARTS OF CHINA	139,747	18,794	0
LOS VILOS	OTHER PARTS OF KOREA	55,490	18,230	0
LOS VILOS	OTHER PARTS OF PHILIPPINES	14,538	18,236	0
LOS VILOS	OTHER PARTS OF JAPAN	440,437	17,171	0
MICHILLA	HUELVA	33,660	12,150	1
MICHILLA	OTHER PARTS OF BULGARIA	8,319	15,813	1
MICHILLA	OTHER PARTS OF GERMANY	25,318	13,538	1
MICHILLA	OTHER PARTS OF BRAZIL	8,264	8,027	0
MICHILLA	OTHER PARTS OF CHINA	158,012	18,681	0
MICHILLA	OTHER PARTS OF KOREA	67,247	18,032	0
MICHILLA	OTHER PARTS OF JAPAN	299,455	16,932	0
PATACHE	HUELVA	33,275	11,781	1
PATACHE	OTHER PARTS OF INDIA	158,173	19,490	0
PATACHE	OTHER PARTS OF BULGARIA	19,850	15,445	1
PATACHE	OTHER PARTS OF GERMANY	31,773	13,169	1
PATACHE	OTHER PARTS OF CHINA	495,796	18,491	0
PATACHE	OTHER PARTS OF KOREA	55,770	17,664	0
PATACHE	OTHER PARTS OF JAPAN	293,609	17,664	0
PUERTO ANGAMOS	BUSAN CY (PUSAN)	533	17,910	0
PUERTO ANGAMOS	CALLAO	3,678	1,517	0
PUERTO ANGAMOS	HONG KONG	2,874	19,593	0
PUERTO ANGAMOS	HONG KONG – TAIWAN	1,831	19,593	0
PUERTO ANGAMOS	HONG KONG - THAILAND	716	19,593	0
PUERTO ANGAMOS	KEELUNG	1,199	18,857	0
PUERTO ANGAMOS	MONTREAL	653	9,890	1
PUERTO ANGAMOS	OTHER PARTS OF CHINA	7,202	18,652	0
PUERTO ANGAMOS	OTHER PARTS OF NAMIBIA	7,315	11,517	0

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(*continued*)

PORT OF ORIGIN	PORT OF DESTINATION	GANGUE CONTENT	NAUTICAL DISTANCE	MARITIME ROUTE
PUERTO ANGAMOS	OTHER PARTS OF GEORGIA	722	16,532	1
PUERTO ANGAMOS	OTHER PARTS OF MALAYSIA	844	19,676	0
PUERTO ANGAMOS	OTHER PARTS OF THAILAND	1,431	20,763	0
PUERTO ANGAMOS	OTHER PARTS OF VIETNAM	747	20,316	0
SAN ANTONIO	KEELUNG	1,095	18,560	0
SAN ANTONIO	OTHER PARTS OF CHINA	2,504	18,778	0
VALPARAISO	OTHER PARTS OF CHINA	3,844	18,773	0
VENTANAS	DAIREN	46,942	19,129	0
VENTANAS	HUELVA	92,371	12,913	1
VENTANAS	OTHER PARTS OF FINLAND	7,829	15,401	1
VENTANAS	OTHER PARTS OF INDIA	198,924	18,167	0
VENTANAS	OTHER PARTS OF BULGARIA	63,417	16,576	1
VENTANAS	OTHER PARTS OF GERMANY	8,021	14,300	1
VENTANAS	OTHER PARTS OF BRAZIL	164,850	7,019	0
VENTANAS	OTHER PARTS OF CHINA	462,638	18,799	0
VENTANAS	OTHER PARTS OF KOREA	117,590	18,302	0
VENTANAS	OTHER PARTS OF JAPAN	264,105	17,265	0
VENTANAS	OTHER PARTS OF SWEDEN	8,150	15,265	1
VENTANAS	OTHER PARTS OF TAIWAN	7,784	18,616	0
VENTANAS	SHANGHAI	31,455	18,799	0

Source: Own elaboration.

Appendix E

Chile: GHG emissions generated by the sea transportation of the gangue content of copper concentrates exported, by importing country and for four scenarios for sensitivity analysis; 2014.

IMPORTING COUNTRY	SCENARIO FOR SENSITIVITY ANALYSIS			
	A	B	C	D
	(ton of CO2-eq)			
GERMANY	23,747	20,779	28,497	24,935
BRAZIL	37,334	32,001	44,801	38,401
BULGARIA	30,132	26,365	36,158	31,638
CANADA	68	60	82	72
CHINA	609,663	522,569	731,596	627,082
SOUTH KOREA	148,157	126,991	177,788	152,390
SPAIN	41,028	35,900	49,234	43,080
PHILIPPINES	4,110	3,522	4,931	4,227
FINLAND	10,650	9,319	12,780	11,182
GEORGIA	126	110	151	132
NETHERLANDS	522	457	627	548
HONG KONG	873	748	1,048	898
INDIA	261,665	224,284	313,998	269,141
JAPAN	491,224	421,049	589,469	505,259
MALAYSIA	257	221	309	265
MEXICO	626	536	751	643
NAMIBIA	5,239	4,490	6,287	5,389
PERU	196	168	236	202
SWEDEN	7,205	6,304	8,646	7,565
TAIWAN	9,209	7,894	11,051	9,472
THAILAND	678	581	814	697
VIETNAM	235	202	282	242
TOTAL	**1,682,946**	**1,445,551**	**2,017,783**	**1,903,389**

Source: Own elaboration.

Appendix F

Chile: GHG emissions generated from smelting and refining copper exported concentrates at the 22 importing countries; 2014.

IMPORTING COUNTRY	COPPER PROCESSED	EMISSIONS RATE	GHG EMISSIONS
	(ton refined Cu)	(ton CO2-eq /ton Cu)	(ton CO2-eq)
CHINA	917,245	0.65	596,209
JAPAN	783,348	0.75	587,511
INDIA	389,699	1.09	424,772

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IMPORTING COUNTRY	COPPER PROCESSED	EMISSIONS RATE	GHG EMISSIONS
SOUTH KOREA	225,616	0.71	160,187
BRAZIL	137,271	0.54	74,126
SPAIN	130,299	0.38	49,513
BULGARIA	71,322	0.46	32,808
GERMANY	62,443	0.52	32,470
FINLAND	25,217	0.69	17,400
SWEDEN	17,821	0.67	11,940
TAIWAN	14,185	0.64	8,898
NAMIBIA	13,990	0.64	8,775
PHILIPPINES	7,466	0.64	4,683
PERU	3,834	0.64	2,405
MEXICO	3,506	0.64	2,199
NETHERLANDS	1,671	0.64	1,048
HONG KONG	1,481	0.64	929
THAILAND	1,106	0.64	694
MALAYSIA	385	0.64	241
CANADA	380	0.64	239
GEORGIA	372	0.64	233
VIETNAM	203	0.64	128

Source: Own elaboration.

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