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Green Window of Opportunity Through Global Value Chains of Critical Minerals: An Empirical Test for Refining Copper and Lithium Industries.

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Abstract

Minerals are critical for the current energy transition since new clean technologies intensively use a large variety of them. But at the same time, mineral production contributes to a large extent to CO₂ world emissions. This dilemma constitutes one of the main challenges for the current techno-economic paradigm shift and, opens green windows of opportunity (GWO) for developing countries.

One option to tackle this dilemma is pricing CO₂ emissions to induce a restructuring of the mineral global value chains (GVCs) towards minimizing CO₂ emissions. The new trade–environmental regulations, such as the cross-border adjustment mechanism of the European Union, point in this direction. In this context, countries with cleaner energy matrixes and the ability to vertically integrate the production of minerals (avoiding emissions) present a competitive advantage.

This paper empirically assesses whether pricing CO₂ emissions along the GVCs could open a GWO in the copper and lithium processing industries for latecomers. The methodology consists of accounting for the CO₂ emissions along the GVCs of the Leader (China) and First-Follower (Chile) countries, pricing the CO₂ emissions and incorporating them into each production cost vector. The catching-up process is evaluated by the production cost convergence once CO₂ emissions are considered.

The results show that a carbon price of US\$96.3/tCO₂e¹ reduces the cash cost gap of copper processing between Chile and China from 232% to 25%. In turn, this price enlarges the cost competitiveness advantage of Chile at producing lithium carbonate and allows the convergence of Chile in the lithium hydroxide production. Once the CO₂ emission value are incorporated into the cash cost vector, producing lithium carbonate and hydroxide in China vis á vis Chile is 69.5% and 5.4% more expensive respectively. Therefore, the study shows that GWOs in the mineral processing industries can be opened for developing countries conditional to favorable technology and endowments. The catching up result is very sensible to the carbon price level and the scope of priced CO₂ emissions.

J.E.L. F61, F64, F68, L72, Q37, Q56, Q58

Keywords: Green window of opportunity, global value chains, critical minerals.

¹ ETS EU average price 2022.

I. Introduction

The energy transition from fossil fuels technologies to low-carbon technologies constitutes a techno-economic paradigm shift and one of the main challenges for the world (Dosi, 1982); (Freeman, 1992). As in every paradigm shift, "windows of opportunities" open for latecomers (Perez & Soete, 1988); (Lee & Malerba, 2017) with which increases the probability of rent redistribution between incumbents and latecomers given that the paradigm shift reduces the advantage of the former ones, which establishes a favorable context for a creative destruction process (Aghion & Howitt, 1992). Recently, it has been stated the concept of green window of opportunity (GWO) to define the bounded period in which a latecomer country can catch up with the industry leader as a consequence of structural changes in the technology, market or institutional conditions, triggered by environmental drivers (Lema, et al., 2020).

The literature has shown through study cases that GWO can be taken by emerging countries and, hence, they are not just reserved for developed countries (Lema & Rabelloti, 2023). However, most of the success cases come from China, a country that presents unique characteristics, such as its economic scale, which does not necessarily allow for to extrapolation of these results (Lema, et al., 2020); (Landini, et al., 2020). Indeed, China has become the leader in several key industries for the energy transition, such as solar panel, wind turbines and electric cars, and owns a dominant position in intermediate industries that play a critical role in manufacturing these technologies, one particularly relevant is the mineral processing industry.

The mineral processing industry plays a key role in the ongoing energy transition since minerals are critical for the production of the new clean technologies and they need to be processed (Valverde, et al., 2023). In almost all the cases² the processes include smelting and refining mineral ores and, in several cases, processing seems to be the bottleneck stressing the minerals' criticality due to the high production concentration in one or two countries. For instance, China owns over 40% of the processing installed capacity to smelt and refine copper, cobalt, lithium, and rare earths, which boosts the criticality level of these minerals (International Energy Agency, 2021). Additionally, smelting and refining minerals are very energy-intensive processes, which induce the emissions of large amounts of CO₂ through fuel and electricity consumption. Even more, the smelting of some specific mineral ores has been defined as hard-to-abate processes since they employ carbon-intensive reactive substances with a not direct substitute, such as steelmaking (Ahman, et al., 2018).

Thereby, the energy transition requires larger amounts of critical minerals but demands reducing CO₂ emissions. This trade-off defines what we call the puzzle of the critical minerals in the energy transition, which can be addressed through two main channels. On the one hand, technological change could reduce the CO₂ emissions in the mining sector by creating new low-carbon technologies for producing minerals or technologies with a lower consumption intensity of minerals, which would decrease the total emissions. On the other hand, global value chains (GVCs) restructuring could reduce CO₂ emissions just by re-locating production processes from countries environmentally inefficient (high-carbon emissions) to countries environmentally efficient (low-carbon emissions).

² For instance, lithium from brines is treated in chemical plants.

This paper focuses on the GVC restructuring channel. We study whether the energy transition could open a GWO for latecomers' countries in the mineral processing industry. Specifically, we test if constraining the CO₂ emissions intensity could diminish the cost competitiveness gap between China and latecomers and, in this way, foster the vertical integration³ of mining operations in rich minerals countries. The underlying hypothesis is that the ongoing techno-economic paradigm shift, plus the economic development level gotten by China, should tend to vanish the Chinese competitive advantages during the next years, which could open a temporal window for the latecomers. Specifically, the international trade-environmental framework that several countries are promoting to accelerate the energy transition would reduce Chinese competitiveness since its energy matrix is more intensive in carbon emissions than other emerging countries that produce and process mineral ores, such as Zambia, Congo D.R, Argentina, Chile and Peru. An example of this kind of policies is the Carbon Border Adjustment Mechanism implemented by the European Union (Bellora & Fontagné, 2023). In addition, Chinese wages have increased in line with the sustained growth of the economy during the last decades, which reduces its competitive advantage given by the low labor costs⁴ (Li, et al., 2012); (Ge & Tao Yang, 2014).

Two particularities of the global value chains (GVCs) in the mineral processing industry would boost the effect of pricing CO₂ emissions. On the one hand, slicing the first stages of the GVCs in which minerals participate is environmentally inefficient since most of the minerals concentrates have low ore grades, with which shipments mainly transport gangue⁵. Therefore, a carbon price would make gangue transportation more expensive and would contribute to reducing the operational cost gap between China and latecomers. On the other hand, smelting and refining are highly energy-intensive processes that consume large quantities of energy, with which countries having a cleaner energy matrix have a competitive advantage in a low-carbon paradigm. For instance, the Chinese electric grid has a higher emission factor than other emerging countries that produce and process mineral ores, such as Zambia, Congo D.R, Argentina, Chile and Peru. Thereby, a carbon price that covers all emissions through the GVC (scopes 1, 2 and 3)⁶ of the metallurgy sector would allow to increase the latecomers' competitiveness against China. Furthermore, the reallocation of the smelting and refining installed capacity would translate into a reduction of global CO₂ emissions.

Figure 1 summarizes the conceptual framework supporting the hypothesis of a GWO emergences. In a nutshell, the GWO for developing countries rich in minerals is given by a GVC restructuration triggered by an institutional change (cross-border carbon price). Pricing and incorporating CO₂ emissions into the production costs reduces the cost gap between the leader and the latecomer countries. This is because the global value chain of latecomers emits less CO₂ in processing and transporting stages. Additionally, the salary growth trend in China is reducing its competitiveness.

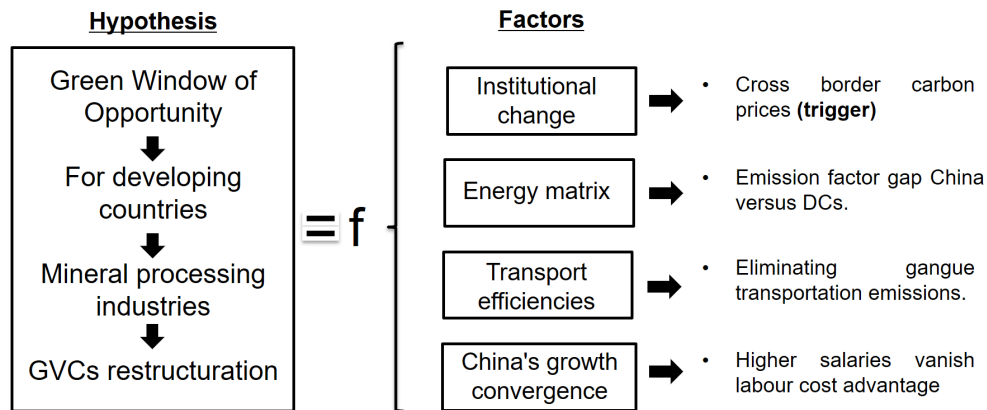
³ Extraction + smelting + refining.

⁴ Labor cost represents the second higher cost of smelting after the energy cost (Chilean Copper Commission, 2021).

⁵ Material without economic value.

⁶ Scope 1 refers to the emissions directly produced as consequence of the productive process. Scope 2 emissions are those induced through the electric consumption and Scope 3 refers to emissions triggered through the supply chain as a consequence of the intermediate inputs consumption.

Figure 1: Conceptual Framework



Source: Own elaboration.

It is worth noting that the catching-up mechanism proposed in this paper is static. I.e., the institutional change is a shock that changes the relative price automatically from one period to the next period. Therefore, it is not considered any dynamics on how the shock could modify the technology of production of the leader and latecomers.

The analysis is empirically performed for the copper and lithium industries as study cases. The methodology adopts a GVC perspective to estimate the CO₂ emissions gap between the GVC of the leader country (China in both cases) and the first-follower (Chile in both cases). In the copper case, the analysis is performed by comparing the CO₂ emissions of copper cathodes produced in China by employing Chilean copper concentrate vis a vis copper cathodes produced in Chile. Meanwhile, in the lithium case, the comparison is between the CO₂ emission of producing refined lithium (carbonate and hydroxide) in China by employing Australian spodumene versus producing refined lithium in Chile by using local lithium resources from brines. Once the CO₂ emission gap for each mineral is sized, the next step consists of pricing it and incorporating it into the direct cost gap between the Leader and Follower GVC. The results show that a carbon price of US\$96.3/tCO₂e reduces the cash cost gap of copper processing between Chile and China from 232% to 25%. In turn, this price enlarges the cost competitiveness advantage of Chile at producing lithium carbonate and allows the convergence of Chile in the lithium hydroxide production. Once the CO₂ emission value are incorporated into the cash cost vector, producing lithium carbonate and hydroxide in China vis á vis Chile is 69.5% and 5.4% more expensive respectively.

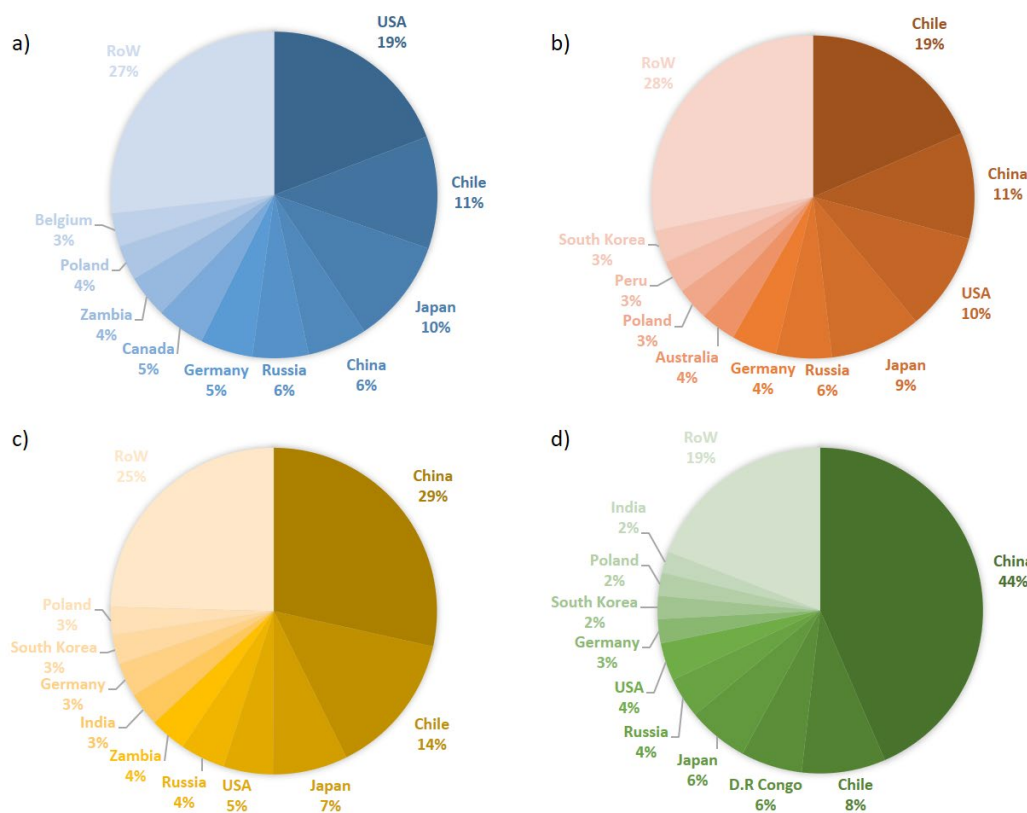
The paper follows with Sections II and III presenting the copper and lithium cases respectively. Then, Section IV introduces the methodology and data used to estimate the CO₂ emissions from the different GVCs for refining copper and lithium. Section V presents the results and Section VI the final remarks.

II. The Global Value Chains (GVCs) of the Copper Metallurgy Industry

In line with the globalization wave, the copper industry has progressively structured along global value chains (GVCs) (Pietrobelli, et al., 2018). This means that production stages from the extractive process to industrial processes are performed in different countries according to their comparative advantages. This production structure has led to the concentration of copper ore processing during the last three decades (Kang, et al., 2022), arising China as the

leader. As a collateral effect, copper ore-producing countries have specialized in the extractive stages and de-industrialized their economies. Figure 2 illustrates these changes in the refined copper industry during the last three decades through the market share evolution. Specifically, graphs a), b), c) and d) illustrate the market share of the top 10 producers of copper cathodes for the years 1992, 2002, 2012 and 2022 respectively.

Figure 2: Evolution of the market share in the Refined Copper Industry.



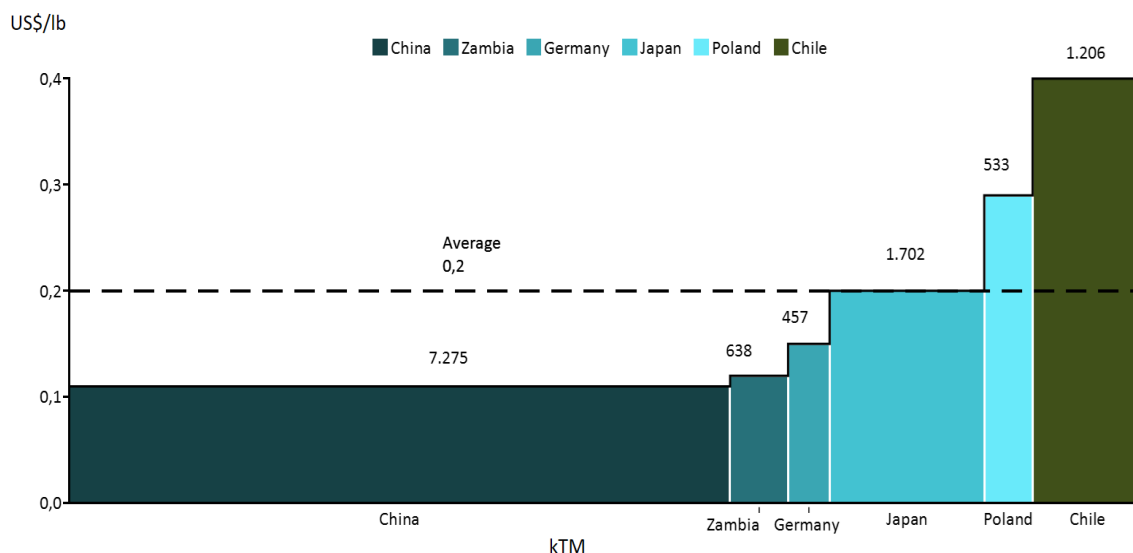
Source: Own elaboration based on Copper Chilean Commission Statistics.

Figure 2 highlights the following facts: i) In 30 years China jumped from 8% to 43.5% of the market share in the copper refining industry, ii) Chile is the first follower with 8% of the market share, however, in 2002 was the leader with 19%, iii) The market share of the rest of the world (RoW) was majoritarian until 2012 when China overpasses it, and iv) Excepting D.R Congo, all other major copper concentrate producers reduced their market share.

The structural change of the copper metallurgy industry was led by the market power that China built during the last decades. This was leveraged in its considerably lower operational costs explained by its lower energy and labor costs, which constitute the main costs of metallurgy processes (Chilean Copper Commission, 2021). In this regard, Figures 3 and 4 illustrate the world supply curves of copper smelting and refining at the country level, from which it is seen that China dominates both markets in terms of market share/production based on operational costs that are half of the average operational costs in each industry. It is worth noting that this is the mainstream production line of copper cathodes (pyrometallurgy),

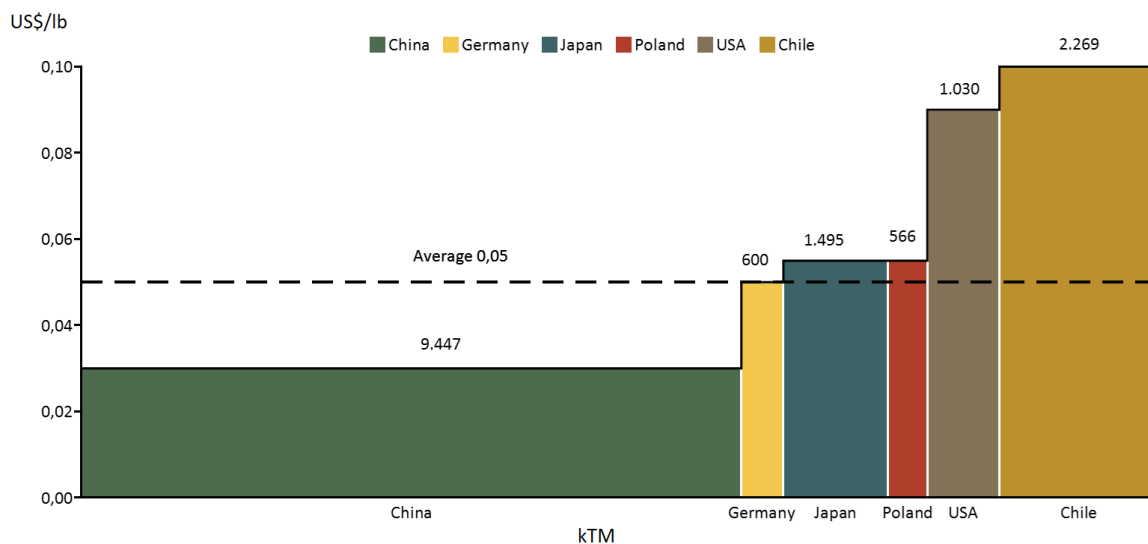
however, copper cathodes also can be obtained through the solvent extraction and electrowinning (SxEw) production line (hydrometallurgy) (Bartos, 2002).

Figure 3: Supply Curve of Copper Smelting for a Group of Selected Countries (2019)



Source: (Pietrobelli & Valverde, 2024).

Figure 4: Supply Curve of Copper Refining for a Group of Selected Countries (2019)



Source: (Pietrobelli & Valverde, 2024).

Nevertheless, China does not have copper ore enough to feed its smelters and, therefore, depends on copper concentrate imports to produce copper cathodes. Indeed, China is the main copper concentrate importer in the world with 54.7% of the total exports. In this regard, most of the copper concentrate used for smelters in China comes from Chile, which positions this global value chain as the most relevant in the copper cathodes industry (43.5%

of the world production of copper cathodes). Chile has been the leader of the copper ore industry during the last four decades and its current market share reaches 24.7% (2022). In turn, China has been the main importer of Chilean concentrate during the last two decades, demanding 68.7% of the Chilean production in 2022, equivalent to 2,018 kMT⁷.

The second most important supply chain is the vertically integrated production of copper cathodes in Chile, capturing 8% of the market. Here, the copper concentrate is domestically processed until copper cathodes, which are (mainly) exported to China (43%). It seems paradoxical that Chile is the first-followers of this industry since it presents the highest direct production costs according to Figures 3 and 4. However, this is explained because Chile still owns a large share of Sx-Ew cathode production (66% of the refined copper production in 2022), which partially compensates for the low competitiveness in the mainstream production line. Indeed, Chile is the major producer of Sx-Ew cathodes accounting for 39% of the global market. The Sx-Ew cathodes are obtained through a hydrometallurgical process by which copper oxides are leached, extracted by solvent, and, finally filtered using an electrowinning technique (Bartos, 2002).

Thereby, the copper cathodes are produced along two main global value chains (GVCs). The Leader GVC is given by the copper concentrate production in Chile, the copper cathode production in China and the use of copper cathodes in China (CHL - CHN – CHN). Meanwhile, the Follower GVC is depicted by the copper concentrate production in Chile, the copper cathode production in Chile and the use of copper cathodes in China (CHL – CHL – CHN).

Although both GVCs deliver the same final product (copper cathode), they differ in terms of the induced and emitted CO₂, which is a factor that increasingly gains relevance in shaping competitiveness given the new low-carbon techno-economic paradigm. The CO₂ emissions differential is explained by both the emissions intensity in processing copper concentrate and the transportation of the copper products. Whilst the CO₂ emission of the extractive processes and the basic metal industry are assumed equal for both GVCs since copper ores come from Chile and copper cathode are employed in China in both GVCs.

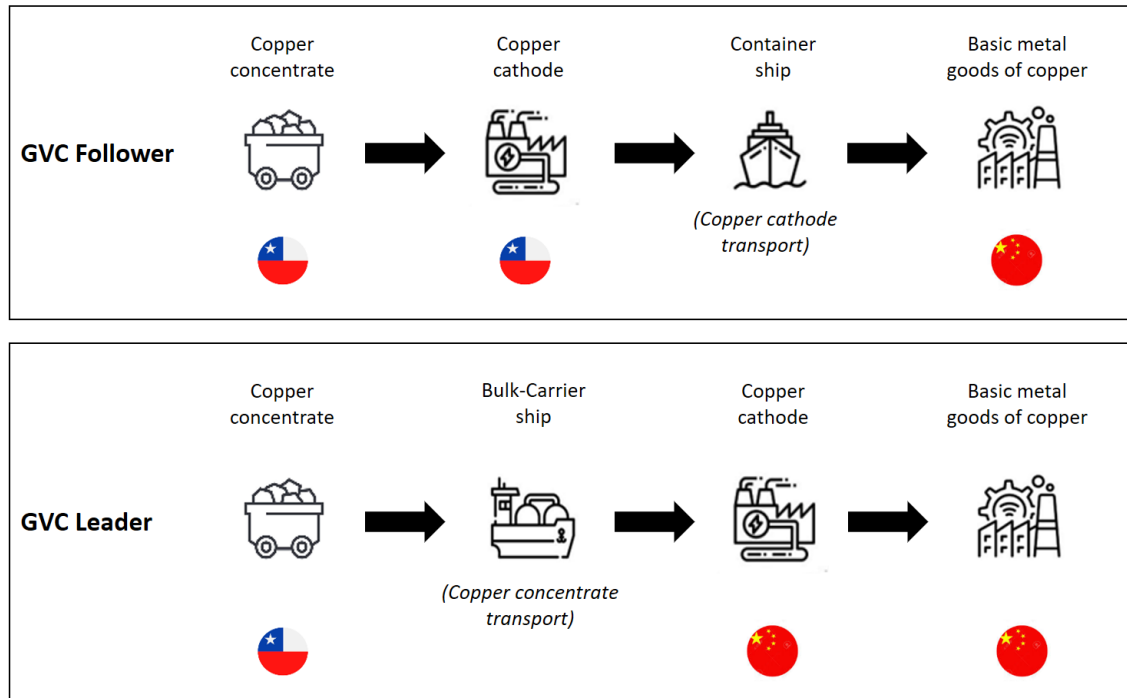
In the case of the Follower GVC, both components are less intensive in CO₂ emissions than the leader GVC due to the cleaner energy matrix of Chile and the higher efficiency of transporting copper cathodes instead of copper concentrate. Specifically, the emission factor of smelting and refining in China is 97%⁸ higher than in Chile. In turn, copper concentrate exports from Chile to China means transporting 28% of copper and 72% of gangue (on average) (Chilean Copper Commission, 2023). I.e., most of the shipment transport material without economic value, which in part is profitable because the negative externalities of CO₂ emissions are not incorporated in the price vector. Differently, copper cathode exports from Chile to China contain 99.99% copper, with which the transportation inefficiencies vanish.

In both the Follower and Leader GVCs the assumption is China uses copper cathodes for its local industry of basic metal goods. Figure 5 illustrates the composition of both GVCs.

⁷ All statistics are taken from the Yearly Statistical Book of the Chilean Copper Commission 2023.

⁸ According to (Chilean Copper Commission, 2022) and (Sturla, et al., 2020).

Figure 5: GVC Composition of the Copper Cathodes Production



Source: Own elaboration.

III. The Global Value Chains (GVCs) of the Lithium Refining Industry

When lithium industry is analyzed, there are two key considerations to have in mind. First, the production technology remarkably differs depending on the primary source of lithium. Extracting lithium from brines and its processing until to obtain battery-grade lithium is an inherently chemical process, in which lithium is concentrated through solar evaporation and reagents, after which is sent it to chemical plants for refining through solvent extraction (Tran & Luong, 2015). Differently, extracting lithium from ore is a classic mining technology, which includes crushing, separation, flotation and leaching, among others, of the mineral, after which the lithium concentrate goes to the smelter and refinery plants to produce battery-grade lithium (Gao, et al., 2023). Therefore, the primary source of lithium has direct effects on the production function of the operations and the supply chains.

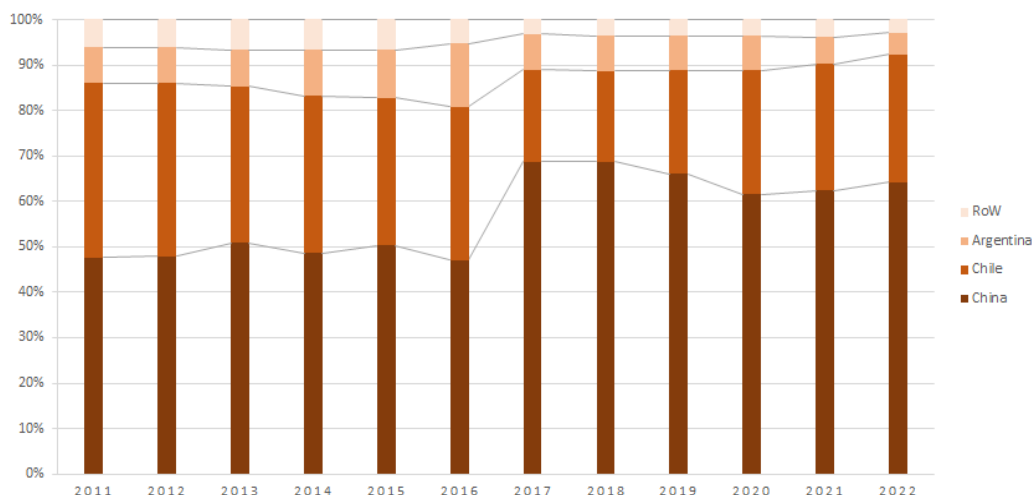
Second, although the lithium industry has structured along GVCs during the last decades, it was not until a few years ago that the trade through GVCs evidenced a boom. This phenomenon obeyed the structural change experienced by the lithium industry during the last years when the scale and composition of the market changed as a consequence of the rise of demand for rechargeable ion-lithium batteries for electric vehicles. From 2011 to 2022 the lithium market expanded almost 6 times and lithium hydroxide gained market share until reaches 27.6%. In terms of lithium uses, electric batteries represented 23% in 2011, meanwhile, they reached 71% in 2020 (Pietrobelli & Valverde, 2024).

The structural change evidenced in the lithium market led to the concentration of the lithium industry, both in the extraction and processing stages, with Australia and China as the main

winners. During the period 2011 – 2022, Australia expanded its market share in the extractive lithium industry from 35% to 52%, where almost all the production was exported to be processed in China. In accordance, China increased its market share in the refined lithium industry from 47% to 64% during the same period. Thereby, the lithium ore production line became the main one, displacing the integrated production line of refined lithium from brines. In consequence, the participation of integrated refined lithium production from brines considerably dropped. Chile, the first-follower in refined lithium production, diminished market share from 38% to 28% during the analysis period. In consequence, the GVC conformed by Australian spodumene, Chinese refined lithium and Chinese lithium cathode (AUS-CHN-CHN) took the leadership of the industry to the detriment of the GVC conformed by Chilean concentrate brine, Chilean refined lithium and Chinese lithium cathode (CHL-CHL-CHN).

Figure 6 illustrates the evolution of the market shares of refined lithium supply by countries for the period 2011 - 2022.

Figure 6: Evolution of the Market Shares of the Refined Lithium Market



Source: Own Elaboration based on S&P Market Intelligence.

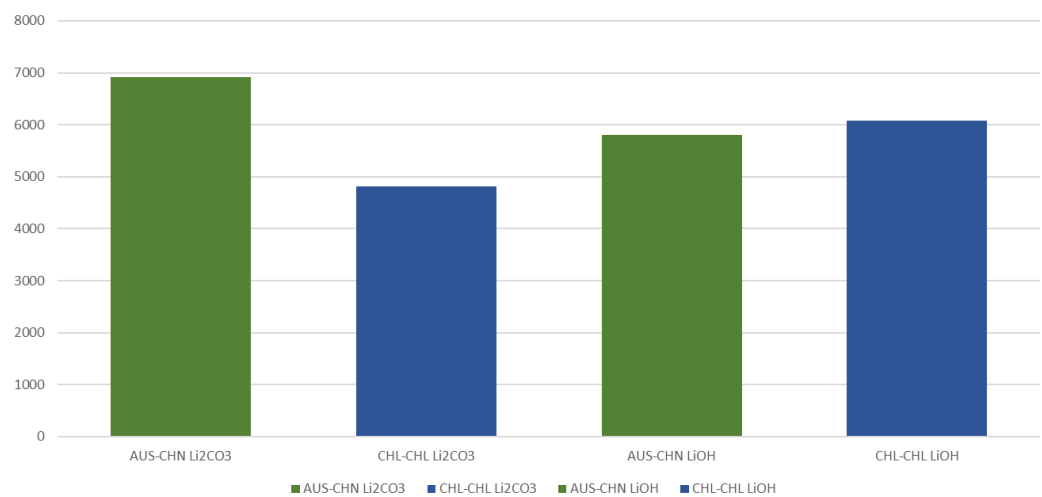
Figure 6 shows that, although China already was the leader of the refined lithium industry before of the market shift, the market share difference regarding Chile significantly grew after the lithium boom. However, the larger market share of China was not explained by a marginal cost convergence with Chile, since the costs of producing refined lithium remained lower in the South American country, but because of the lithium price rise. Indeed, the lithium market shortage increased lithium prices to the point that most of the projects could enter the market, with which high-cost operations from lithium ore captured most of the market during the last few years. Therefore, costs have played a minor role in the industry competitiveness, measured as the market share, during the last years. Nevertheless, as the lithium market adjusts and the price reduces the operations with the highest direct cost exit the market, with which cost structure becomes relevant. Indeed, during the second semester of 2023, the lithium price decreased by 69%, stressing the lithium ore supply.

The technology differences stated in the beginning of this section directly impact the cost competitiveness of the operations. The literature points out that on average producing

lithium carbonate battery grade from lithium brine resources is cheaper than from lithium ore, meanwhile, lithium hydroxide production is the other way around. Meanwhile, for the lithium hydroxide production the cost competitiveness inverts. The poorer performance of lithium brine projects in producing lithium hydroxide is due to the technical impossibility of directly producing lithium hydroxide from brines, which makes it mandatory to produce lithium carbonate as an intermediate good. Oppositely, the lithium ore line allows the production of both lithium carbonate and lithium hydroxide (International Energy Agency, 2021); (Jiménez & Sáez, 2022); (Chilean Copper Commission, 2023).

Figure 7 illustrates the direct cost differential between producing lithium carbonate and hydroxide through the Leader GVC (AUS – CHN) and the Follower GVC (CHL – CHL). These production costs corresponds to an own estimate by using information at the industry and operation level⁹ for the year 2022. The relative prices between Chinese and Chilean refined lithium are according to the literature, i.e., the cost of producing lithium carbonate in Chile is significantly lower than in China, meanwhile, producing lithium hydroxide is cheaper in China than in Chile.

Figure 7: Cash Cost of Lithium Carbonate and Hydroxide Production by GVC



Source: Own Elaboration based on S&P Market Intelligence, SQM Financial Statement 2022 and (Chilean Copper Commission, 2023).

The previous cost competitiveness analysis shows that the Follower GVC produces lithium carbonate 40% cheaper than the Leader GVC. In turn, the production cost of lithium hydroxide is almost identical. Nevertheless, the cost competitiveness does not reflect the induced and emitted CO₂, where the Leader GVC emits considerably more CO₂ than the Follower GVC. The literature points out that one ton of lithium carbonate from spodumene emits several times more than one from brines. For instance, (International Energy Agency, 2021) estimates the differential between 3 and 4 times, (Kelly, et al., 2021) between 2 and 7, and (Gao, et al., 2023) between 9 and 60. This difference is explained because refined lithium production from spodumene is a process highly intensive in energy consumption in

⁹ We employed the S&P Market Intelligence as base data, however, we complemented and adjusted this information with (Chilean Copper Commission, 2023) and the Financial Statements of SQM (2022).

both extraction and refining processes, meanwhile, lithium from brines is based on chemical reactions, which do not intensively consume energy.

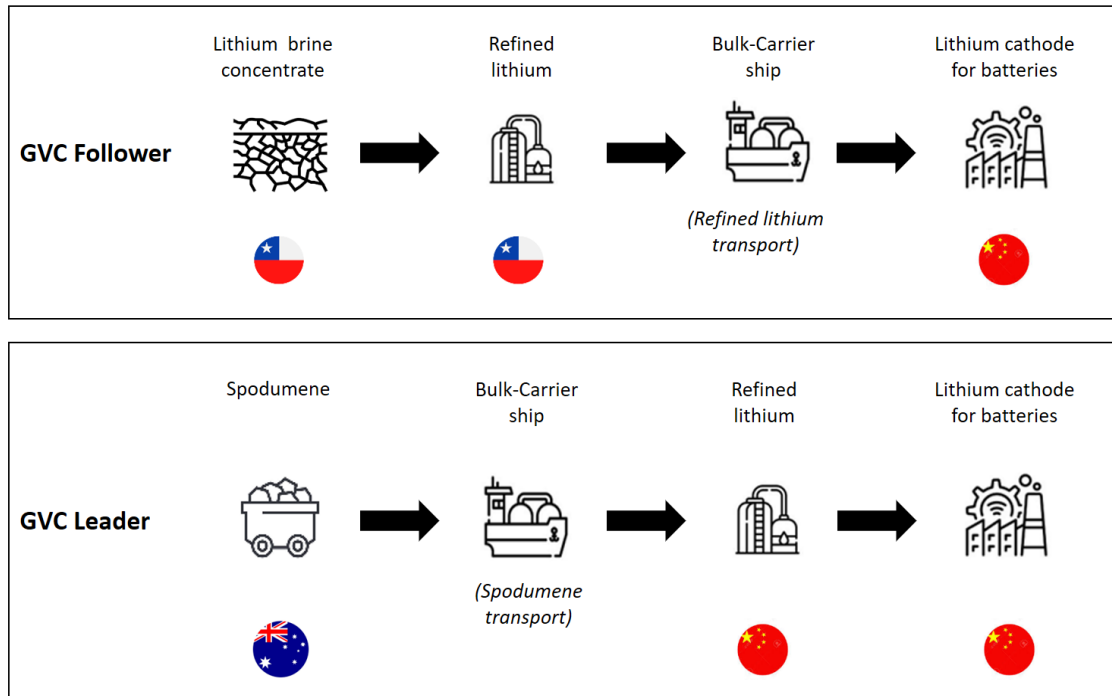
Moreover, the GVCs configuration also contributes to the environmental gap since slicing the first stages of the GVC obeys a cost optimization, but does not consider environmental efficiency. In the case of the Follower GVC, the first stage is pumping of the brine from the Salar de Atacama, which precipitates through pipes into large and shallow pools for its concentration through solar evaporation. Therefore, most of the energy employed in this process is zero CO₂ emissions since production takes advantage of the exosystemic services provided by the solar radiation. The second stage consist of purifying and refining the concentrated lithium brine through solvent extraction in the chemical plant located near to the Antofagasta until obtain lithium carbonate. This process is the most energy intensive of the brine production line given the electricity consumption. However, compared with the other productive factor energy is not very relevant (around 10% of the direct cost). At this point, a share of the lithium carbonate is used as intermediate good for the production of lithium hydroxide and the rest exported (most of it). So, the third stage for the exported lithium carbonate is the maritime shipment, which employs bulk carriers to transport it from Chile to (mainly) China. According to the National Custom Service of Chile during 2022 73.6% of the lithium carbonate exports of Chile had China as final destination and all of it came from Antofagasta. For the hydroxide production line, lithium carbonate is refined by using calcium hydroxide as reactant and a sequence of thermic processes, which is 19% more intensive in energy consumption than lithium carbonate production. The third stage of lithium hydroxide export is identical than the lithium carbonate case.

In the case of the Leader GVC, the first stage consists of extracting and processing the mineral ore, which includes different tasks such as crushing, grinding, separation, flotation, calcination and leaching, among others, and its outcome is the lithium concentrate, or spodumene, which contains in average 6% of lithium oxide. The second stage is the spodumene maritime shipment from Australia to China for its refining. The spodumene transportation is carried on through bulk-carrier vessels, where each shipment transports on average 15,000 tons¹⁰ and, hence, only 900 tons of lithium oxide. In consequence, almost all CO₂ emissions are triggered by no-value material transportation (gangue). The third stage consist of the spodumene refining in Chinese smelters to produce either carbonate or hydroxide. Both processes are very intensive in energy consumption and intermediate goods, such as sulfuric acid and silicates (Gao, et al., 2023); (Alhadad, et al., 2023).

In both the Follower and Leader GVCs the assumption is China uses the refined lithium products for its local industry of lithium cathodes. Figure 8 illustrates the composition of both GVCs.

¹⁰ <https://www.greencarcongress.com/2021/02/20210209-roskillspodumene.html>

Figure 8: GVC Composition of the Refined Lithium Production



Source: Own elaboration.

IV. Methodology and Data

This section presents the methodology and data employed to empirically test the idea of the green window of opportunity (GWO) for both the copper and lithium mineral processing industries. Following (Lema, et al., 2020), we define the GWO as the bounded period in which the latecomer (Chile) can converge in terms of direct production cost (catching up) with the leader (China) in processing copper and lithium, as a consequence of pricing CO₂ emissions (institutional change). Nevertheless, as the previous sections introduced, mineral processing industries are structured along GVCs and, hence, CO₂ emissions must be accounted for at all stages and not only in the refining process. In practical terms, do not price CO₂ along the GVC fosters carbon leakages and multinational companies could arbitrage in terms of CO₂ emissions just by sending the emission-intensive stages to countries with weaker environmental regulation.

The cost convergence analysis proposed in this study is carried out from a GVC perspective, which means estimating the carbon emission of the different stages presented in Figures 5 and 8. Specifically, the empirical exercise consists of determining the CO₂ emissions gap between the Leader GVC and Follower GVC and estimating the effect of an international carbon price on the cost competitiveness of both supply chains.

In the copper case, the Leader GVC is structured through the copper concentrate production in Chile, the copper cathode production in China and the use of copper cathodes in China (CHL - CHN – CHN). Meanwhile, the Follower GVC is defined by the copper concentrate

production in Chile, the copper cathode production in Chile and the use of copper cathodes in China (CHL – CHL – CHN).

In the Lithium case, the Leader GVC is structured through the Australian spodumene, the refined lithium production in China and the use of the refined lithium by China (AUS-CHN-CHN). Meanwhile, the Follower GVC is defined by the Chilean lithium resources from brines, the refined lithium produced in Chile and the use of the refined lithium by China (CHL-CHL-CHN).

The methodology consists of three sequential steps: i) estimating the CO₂ emissions gap between the Leader and Follower GVCs, ii) pricing these CO₂ emissions, and iii) incorporating the emission value into the direct cost gap of producing refined minerals between the Leader and Follower. The step-by-step is presented in the following subsections.

4.1 CO₂ Emissions Gap

The CO₂ emissions gap in the production of refined minerals between the Leader and Follower GVCs arises from the emission intensity differential in each stage of the GVC. Therefore, we adopt a scope 3 framework to account for CO₂ emissions, where the system is composed of four stages that explain the CO₂ gaps: extraction gap, processing gap, transport gap and use gap¹¹ (Inter-American Development Bank, 2021), such as Equation 1 shows

$$(1) \Delta CO_{2m,l-f} = \Delta E_{m,l-f} + \Delta P_{m,l-f} + \Delta T_{m,l-f} + \Delta U_{m,l-f}$$

Where:

- $\Delta CO_{2m,l-f}$: CO₂ emissions gap between the Leader (l) and Follower (f) GVCs in producing one tone of the refined mineral (m).
- $\Delta E_{m,l-f}$: CO₂ emissions gap between the Leader (l) and Follower (f) GVCs in extracting one tone of the refined mineral (m).
- $\Delta P_{m,l-f}$: CO₂ emissions gap between the Leader (l) and Follower (f) GVCs in processing one tone of the refined mineral (m).
- $\Delta T_{m,l-f}$: CO₂ emissions between the Leader (l) and Follower (f) GVCs in transporting one tone of the refined mineral (m).
- $\Delta U_{m,l-f}$: CO₂ emissions between the Leader (l) and Follower (f) GVCs in using one tone of the refined mineral (m).

We assume that all refined mineral is used as intermediate goods by basic metal industries in China, which implies $\Delta U_{m,l-f} = 0$. Although this is a simplification, it is line with the market share of China in the downstream stages, such as lithium cathode and ion-lithium battery production. Therefore, the analysis is reduced to the upstream stages of the GVC.

¹¹ The extraction, processing and transport are upstream stages, meanwhile the use is a downstream stage.

4.1.1 CO2 Emissions Gap of Extracting Minerals ($\Delta E_{m,l-f}$)

The CO2 emissions of extracting minerals belong to Scope 3 emissions of refined minerals¹² and arise as a coproduct of fossil fuel consumption and energy use. Classic mining operations, such as copper or lithium ore, use most of the fossil fuel in the open pit, meanwhile most of the energy consumption comes from the concentrator plant (Chilean Copper Commission, 2022). In turn, lithium extraction from brines is a low-carbon intensive process that concentrates the CO2 emissions in the consumed energy for pumping brine from the salt flat (Kelly, et al., 2021).

In the copper case, as Figure 4 shows, the emissions associated with the mineral extraction are identical for both Leader and Follower GVCs. This is because the copper concentrate comes from Chile in both cases. Although this is a simplification, it is representative of the export and production flows since China imports 68.7% of the Chilean copper concentrate and Chile only uses domestic concentrates for processing it. Therefore, this stage does not affect the CO2 gap in the copper cathode production between Chile and China.

In the lithium case, as Figure 8 illustrates, the primary source of lithium differs between both GVCs and, hence, also the CO2 intensity of the extraction process. Most of the CO2 emissions of the brine lithium extraction come from the energy employed to pump the brine from the salt flat. Meanwhile, lithium extraction from mineral ores concentrates the emissions in the mining and concentration processes.

According to the literature, the CO2 emissions attached to the lithium extraction from brines range between 0.064 and 0.16 tCO2e/tLiCl (6%)¹³, meanwhile the CO2 emissions from lithium ore extraction are estimated at 0.35 tCO2e/tLi2O (6%). I.e., one ton of spodumene containing 6% lithium oxide (Li2O) emits between 2 and 6 times more CO2 than one ton of concentrate brine containing 6% of lithium chloride (LiCl) (Kelly, et al., 2021). However, one ton of Li2O (6%) is not equivalent to one ton of LiCl (6%) in terms of lithium carbonate equivalent. Indeed, producing 1 ton of lithium carbonate 99.5% (Li2CO3) requires 4 tons of LiCl (6%) and 7.3 tons of Li2O (6%)¹⁴. In this paper, the emission factors employed were 0.091 tCO2e/ tLiCl (6%)¹⁵ and 0.35 tCO2e/tLi2O (6%) for brines and ore extraction respectively.

Formally, the CO2 extraction gap between the Leader and Follower GVCs is given by the emission factor differential of the extracting lithium from brines vis á vis mineral ore, such as Equation 2 shows

$$(2) \Delta E_{m,l-f} = EEF_{m,l} + EEF_{m,f}$$

Where:

· $EEF_{m,l}$: extraction emission factor of the Leader GVC measured as tons of CO2e per tons of mineral $\left(\frac{tCO2e}{t Min}\right)$.

¹² Concentrate mineral is an intermediate good for refined mineral production.

¹³ The differences between the CO2 intensity are given by the method employed to assign emissions to lithium processes/products since potash is produced as coproduct.

¹⁴ Hence, the relationship between LiCl and Li2O is 1:1.8.

¹⁵ Corresponds to the process allocation criteria according to (Kelly, et al., 2021)

· $EEF_{m,f}$: extraction emission factor of the Follower GVC measured as tons of CO₂e per tons of mineral $\left(\frac{tCO_2e}{t\ Min}\right)$.

4.1.2 CO₂ Emissions Gap of Processing Minerals ($\Delta P_{m,l-f}$)

The CO₂ emissions from processing minerals come from the induced emissions through energy consumption (Scope 2) and the direct emissions from fossil fuels use (Scope 1). The classic processing route of mineral ore includes smelting and refining, which are processes highly intensive in energy consumption (Lagos, et al., 2015). This is the route followed by the copper cathode and refined lithium production from lithium ores. Differently, refined lithium production from brines is a less energy-intensive process since continues in the chemical plant, wherein the refining process is carried on through solvent extraction (Tran & Luong, 2015).

In the copper case, as Figure 4 shows, the CO₂ emission gap is explained by the difference in the emission factor of processing in China vis á vis Chile. According to the literature, one ton of copper cathode refined in China emits 1.63 tCO₂e, meanwhile, one ton of copper cathode refined in Chile emits 1.40 tCO₂e (Lagos, et al., 2015). For the present paper, the emission factor of smelting and refining copper in Chile is estimated from production, direct and indirect CO₂ emissions data published by the Chilean Copper Commission¹⁶. Meanwhile, the emission factor of smelting and refining copper in China is estimated by using the direct emission factor reported in the literature (Sturla, et al., 2020) and an estimate of the indirect emissions as a proportion of the former one. Therefore, the emission factors used for mineral processing in Chile and China were 1.23 tCO₂e/tCuEq and 1.7 tCO₂e/tCuEq respectively.

In the lithium case, as Figure 8 shows, the CO₂ emission gap is given by the difference in the emission factor of processing spodumene in China vis á vis processing lithium brine in Chile. According to the literature, producing one ton of lithium carbonate in China from spodumene emits 16.5 tCO₂e¹⁷, meanwhile, one ton of lithium carbonate produced from lithium brine in Chile emits 2.69 tCO₂e (Kelly, et al., 2021). In turn, one ton of lithium hydroxide produced in China from spodumene emits 12.4 tCO₂e, meanwhile, the same ton produced in Chile from lithium brine by using lithium carbonate as intermediate good emits 7 tCO₂e (Kelly, et al., 2021). The present paper employs these emission factors for refined lithium.

Formally, the CO₂ processing gap between the Leader and Follower GVCs is given by the emission factor differential of the refined mineral production in each country. For the lithium case, this is mainly explained by the technological route that is determined by the primary source of lithium. Equations 3 formalizes the processing gap:

$$(3) \Delta P_{m,l-f} = PEF_{m,l} + PEF_{m,f}$$

Where:

· $PEF_{m,l}$: processing emission factor of the Leader GVC measured as tons of CO₂e per tons of

¹⁶ Yearly Statistical Book of the Chilean Copper Commission.

¹⁷ Direct (scope 1) and indirect emissions (scope 2).

$$mineral \left(\frac{tCO2e}{tMin} \right).$$

· $PEF_{m,f}$: processing emission factor of the Follower GVC measured as tons of CO2e per tons of

$$mineral \left(\frac{tCO2e}{tMin} \right).$$

4.1.3 CO2 Emissions Gap of Transporting Minerals ($\Delta T_{m,l-f}$)

The CO2 emissions of transporting minerals belong to Scope 3 emissions of mineral processing and are given by the fossil fuels that feed maritime and land transport. Considering that for both copper and lithium cases, the longer distance by far is the maritime shipment, we focus only on the emission generated by this conveyance.

The CO2 emissions associated to the maritime transportation of minerals are a function of the nominal emission factor of the vessel, the traveled distance and the ore grade/concentration of the transported mineral (Sturla, et al., 2020), as Equation 4 illustrates

$$(4) TEF_m = \frac{VEF_m \cdot d_m}{g_m}$$

Where:

· TEF_m : transporting emission factor measured as tons of CO2e per tons of mineral "m" $\left(\frac{tCO2e}{tMin} \right)$

· VEF_m : vessel emission factor measured as tons of CO2e per tons of transported material per kilometer for mineral "m" $\left(\frac{tCO2e}{tMat \cdot km} \right)$.

· d_m : transport distance for mineral "m" (km).

· g_m : ore grade measured as tons of mineral per ton material for mineral "m" $\left(\frac{tMin}{tMat} \right)$.

Given that the three countries participating in the GVCs of the studied minerals have long internal distances and multiple origin and destination ports, we chose one specific port of origin and destination for each mineral and GVC. The selection was made by identifying the most transited maritime route in each case (statistical mode).

In the copper case, the chosen maritime route was from Antofagasta Port to Shanghai Port since most of the concentrate and cathode exports of Chile come from this region. Indeed, 46% of the copper concentrate production of Chile occurs in the Antofagasta region and 71% of these exports have China as the destination. Whilst, 84% of the copper cathodes are produced in Antofagasta and 42.5% are exported to China¹⁸.

In the lithium case, for the spodumene exports from Australia to China, the chosen maritime route was from Bunbury Port to Shanghai Port since this is the closest port to the Greenbushes mine, which represents more than 50% of the spodumene market, Meanwhile,

¹⁸ These statistics corresponds to an own estimate from the administrative data of the Chilean Custom Service and the Yearly Statistical Book of the Chilean Copper Commission for the year 2022.

for the lithium carbonate and hydroxide exports from Chile to China, the maritime route selected was from Antofagasta Port to Shanghai Port due to 94% and 92% of the lithium carbonate and hydroxide exports, respectively, sail from Antofagasta Port. Moreover, 74.5% of these exports of lithium carbonate have as their destination China, but only 5% of the lithium hydroxide has this same destination¹⁹. For both copper and lithium goods, the port of Shanghai was selected as the destination because of its importance in China's international trade.

Vessel Emission Factor

Regarding the vessel emission factor ($VEF_{m,i}$), this depends on the type and size of the vessel. The two main vessels employed to transport minerals are the Bulk-Carrier and General-Cargo, the former is used for transporting unpacked bulk goods and the latter for packed goods.

The copper concentrate and the refined lithium are shipped by Bulk-Carrier vessels and copper cathodes by General-Cargo vessels. On average, General-Cargo vessels emit more CO₂ per transported ton and kilometer, however, each type of vessel presents different sizes and their environmental efficiency is largely defined by this feature (see Table 1 of the annex).

In the copper case, we calculate the emission factor as a weighted average of all shipments by employing administrative data from the Chilean Customs Service. Specifically, we identify all copper shipments, their value (FOB), volumes (tons), origin city and destination country and, then, we do a matching between the transported load and the emission factors of Table 1 by optimizing the shipment used capacity. Given that each shipment transports other goods, we define one size for large shipments and one size for smaller shipments.

Thereby, copper concentrate shipments transporting up to 35,000 metric tons were assigned to Bulk-Carrier vessels with a load capacity between 35,000 and 59,999 dwt. Meanwhile, shipments over 35,000 metric tons were assigned to Bulk-Carrier vessels with load capacity over 200,000 dwt. Whilst, copper cathode shipments were assigned to General-Cargo vessels with a load capacity of 10,000 dwt or more, which is the larger one.

In the lithium case, Roskill²⁰ reports that the most common vessel employed to transport spodumene from Australia to China is the Handsize bulk-carrier with a load capacity between 10,000 and 34,999 dwt. Therefore, we assume that lithium carbonate and hydroxide shipments from Chile to China use the same type of vessel.

Distances

The shipment distances vary according to the GVCs structure. In the copper case, concentrates and cathodes are shipped from Antofagasta Port in Chile to Shanghai Port in China, which represents a distance of 18,686 km. In the lithium case, the distance traveled by the Australian spodumene from Bunbury Port to Shanghai Port is 7,500 km, whilst the lithium carbonate and hydroxide shipped from Antofagasta Port in Chile to Shanghai Port travel 18,686 km.

¹⁹ These statistics correspond to an own estimate from the administrative data of the Chilean Custom Service for the year 2022.

²⁰<https://www.greencarcongress.com/2021/02/20210209-roskillspodumene.html>

Ore Grades

The ore grades vary according to the type of transported mineral, which in turn is also a function of the GVC structure. In the copper case, the Chilean concentrate owns on average 28% Cu²¹, whilst a cathode contains 99.99% Cu. Therefore, 3.5 shipments of copper concentrate are needed to have one tone of equivalent copper. In the lithium case, spodumene contains on average 6% Li₂O, whilst lithium carbonate contains 99.5% Li₂CO₃ and lithium hydroxide contains 56.5% LiOH. Differently to the copper case, the relation between these chemical compounds is not direct and, hence, it is necessary to convert them to lithium carbonate equivalent (LCE). The conversion shows that 7.3 and 6.4 tons of spodumene are required to produce one ton of lithium carbonate and hydroxide respectively (Kelly, et al., 2021).

Formally, the CO₂ transport gap between the Leader and Follower GVCs is given by the expression

$$(5) \Delta T_{m,l-f} = TEF_{m,l} + TEF_{m,f}$$

Where:

· $TEF_{m,l}$: transporting emission factor of the Leader GVC measured as tons of CO₂e per tons of mineral $\left(\frac{tCO_2e}{t Min}\right)$.

· $TEF_{m,f}$: transport emission factor of the Follower GVC measured as tons of CO₂e per tons of mineral $\left(\frac{tCO_2e}{t Min}\right)$.

In the copper case, the transporting emission factors estimated for copper concentrate and cathode per kilometer from Chile to China were 0.16 and 0.12 tCO₂e/tCuEq, respectively. The ratio between transporting concentrate versus cathodes is similar regarding previous researches (Lagos, et al., 2015), however, the levels are 50% higher than the results exhibited in that paper. Then by multiplying

Meanwhile, in the lithium case, the transporting emission factors per kilometer estimated for the spodumene, lithium carbonate and lithium hydroxide were 0.11, 0.0080 and 0.0084 tCO₂e/tCuEq respectively.

4.2 Pricing CO₂ Emissions

Once the CO₂ emission gap is estimated, the next step consists of pricing it. For this purpose, we employ two different price rates; the market price provided by the Emission Trade System of the European Union (EU ETS) for the year 2022 and the carbon price aligned with the Net Zero goal estimated by the International Energy Agency (IEA) for 2030 (International Energy Agency, 2022). The goal of using one current and one estimated carbon price is to incorporate the foreseen pathway of the CO₂ emission value.

On the one hand, the EU ETS price reflects the CO₂ emissions price of the world's largest carbon market. Given that the carbon price is determined through a market system, it varies across time and depends on the economic activity of the region. After the COVID pandemic,

²¹ Last available data from Copper Chilean Commission (2022).

the price sharply rose overpassing €100/tCO₂e. However, since then the price trend has been negative. The reported average price reported by the World Bank in 2022 was €96.3/tCO₂e²².

In the second hand, the Net Zero - 2030 price reflects the carbon price consistent with reaching the net zero goal in 2050. This price was estimated by the International Energy Agency in €140/tCO₂e (International Energy Agency, 2022) and it has been employ by the European Central Bank in its macroeconomic forecasting²³.

Formally, the value of the CO₂ emissions is given by Equation 6

$$(6) \ \$\Delta CO2_{m,l-f} = \$CO2 \cdot \Delta CO2_{m,l-f}$$

Where:

· $\Delta CO2_{m,l-f}$: value of the CO₂ emission gap between producing refined mineral "m" through the Leader GVC vis á vis the Follower GVC (US\$).

· $\$CO2$: carbon price in US\$.

4.3 Incorporating CO₂ Emissions into the Direct Cost Gap

The last step consists of incorporating the value of the total CO₂ emission gap ($\Delta CO2_{m,l-f}$) into the direct cost gap of producing refined minerals in China (Leader) versus Chile (Follower). Thereby, we can estimate the contribution of pricing CO₂ emission for closing the cost competitiveness gap. In practice, this means adding the value of the CO₂ emissions into the direct cost vector of the mineral processing industry of China since in all cases is the most carbon-intensive production line.

In the copper case, the direct cost gap is given by the treatment and refining cost differential between China and Chile. We estimate treatment and refining costs for year 2022 based on public information published by the Chilean copper Commission (Chilean Copper Commission, 2021); (Chilean Copper Commission, 2022). China presents direct cost of smelting and refining of US\$0.099/lb and US\$0.032/lb respectively. Meanwhile, the Chilean costs reach US\$0.353/lb and US\$0.081/lb respectively. Therefore, the direct cost gap of smelting and refining in Chile vis á vis China is US\$0.3/lb, which means that the metallurgy process in Chile is 3.3 times more expensive than in China.

In the lithium case, two different assessments are performed. On the one hand, the direct cost gap of producing lithium carbonate in China from Australian spodumene is on average²⁴ US\$6,915/ton, meanwhile, the production cost in Chile by using lithium mineral from brines is US\$4,817/ton. I.e., the direct cost of the Leader is 43.5% higher than the Follower. On the other hand, the lithium hydroxide produced by China presents an average direct cost of US\$5,803, whilst the direct cost of Chile reaches US\$6,078. Therefore, the direct cost of the Follower is 4.7% higher than the Leader.

Formally, we introduced the CO₂ emission value into the direct cost as Equation 7 shows

²² <https://carbonpricingdashboard.worldbank.org/>

²³ <https://www.ecb.europa.eu/press/blog/date/2023/html/ecb.blog.230525~4a51965f26.en.html>

²⁴ Weighted by production share.

$$(7) \Delta OC_{m,f-l} = OC_{m,f} - OC_{m,l} - \$\Delta CO2_{m,l-f}$$

Where:

- $\Delta OC_{m,f-l}$: operational cost gap between refining mineral "m" in the Follower country versus the Leader country $\left(\frac{US\$}{t \text{ Min}}\right)$.
- $OC_{m,f}$: operational cost of refining mineral min the Follower country $\left(\frac{US\$}{t \text{ Min}}\right)$.
- $OC_{m,l}$: operational cost of refining mineral min the Leader country $\left(\frac{US\$}{t \text{ Min}}\right)$.

V. Results

This section presents the economic effect of CO2 emission pricing on the cost competitiveness of producing refined copper and lithium between China (Leader GVC) and Chile (Follower GVC). In this regard, we first illustrate the difference in CO2 emission per ton of mineral disaggregated by each stage of the GVC (extraction, processing and transport). Then, we show the effect on the cash cost (C1) of monetizing the CO2 emissions at different carbon prices, with which we assess the catching-up process.

The section follows with subsection 5.1 which exhibits the results for the copper processing industry and subsection 5.2 presents the results for the lithium processing industry.

5.1 Copper Processing Industry

In the copper processing industry, the CO2 emission gap between the Leader GVC (China) and the Follower GVC (Chile) is given by the emission factor differential in processing and transporting the mineral goods. The extracting CO2 emissions are considered identical for both GVCs since most of the primary copper ore comes from Chile. Therefore, the extracting emission gap is null ($\Delta E_{m,l-f} = 0$).

The emission factor gap of smelting and refining copper in Chile vis á vis China is $\Delta P_{m,l-f} = 0.47 \left(\frac{tCO2e}{t \text{ Min}}\right)$. Meanwhile, the emission factor gap of transporting one equivalent ton of copper contained in concentrate vis á vis cathodes is $\Delta T_{m,l-f} = 0.08 \left(\frac{tCO2e}{t \text{ Min}}\right)$. Hence, the total emission gap of producing copper cathodes in China versus Chile is $\Delta CO2_{m,l-f} = 0.55 \left(\frac{tCO2e}{t \text{ Min}}\right)$, which makes Chile more environmentally efficient at producing copper cathodes. Indeed, smelting and refining copper in China by using Chilean concentrate emits 45% more CO2 than producing copper cathodes in Chile. The processing emissions account for 77% of the differential. Figure 9 illustrates the scope 3 unit CO2 emissions generated by producing copper cathodes through the Leader GVC (China) vis á vis the Follower GVC (Chile). Emissions are disaggregated at the stage level.

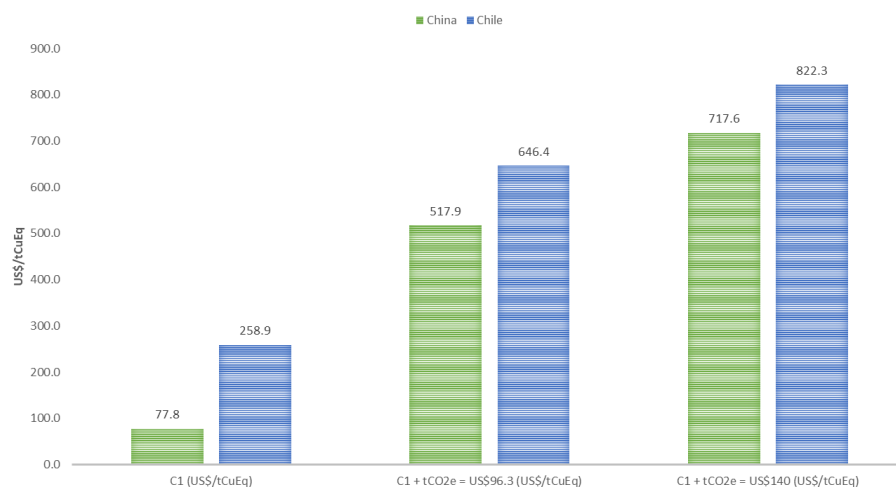
Figure 9: Copper Cathode Unit CO₂ Emissions by GVC stages for the Leader and Follower GVCs.



Source: Own elaboration based on own estimates.

On the other hand, China is considerably more competitive than Chile in terms of production costs. On average, the cash cost of smelting and refining one ton of equivalent copper in China is US\$77, meanwhile the cost in Chile is US\$258.9. I.e., the cathodes cost gap between the Follower and Leader GVCs is 232%. Nevertheless, when CO₂ emissions are priced and incorporated into the cash cost vectors, the cost competitiveness gap sharply reduces. As Figure 10 illustrates, when CO₂ emissions are priced at US\$96.3/tCO₂e the cash cost gap reduces to 25%, and with a carbon price of US\$140/tCO₂e the gap size is 15%.

Figure 10: Cash Cost Gap of Copper Cathode Production by Carbon Price Scenarios



Source: Own elaboration based on own estimates.

In consequence, pricing CO₂ emissions and incorporating them into the cash cost vector significantly reduces the cash cost gap, but it is not enough to get a cost convergence and, in this way, the catching-up of the industry. Nevertheless, this scenario constitutes a benchmark that current and new smelters and refineries can consider to evaluate their operations and projects. For instance, the most efficient smelter in Chile operates with a

cash cost of US\$136.5 per ton, if we add the average refining cost, the copper cathode production reaches US\$185 per ton. Then, if we monetize carbon emissions at US\$140/tCO_{2e}, the cash cost gap size is only 3%.

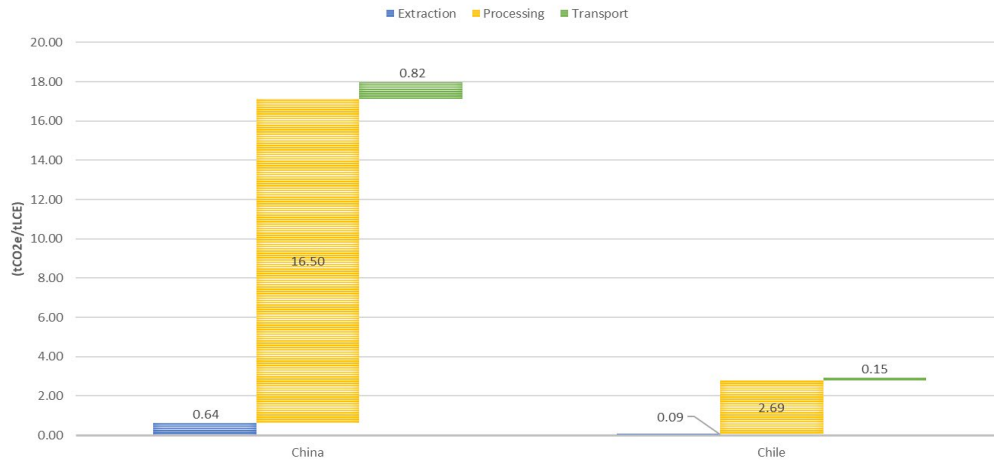
5.2 Catching-up in the Lithium Processing Industry

In the lithium processing industry, the CO₂ emission gap between the Leader GVC (China) and the Follower GVC (Chile) is explained by the emission factor differential in extracting, processing and transporting lithium goods. The processing and transporting emissions differ depending on whether the final lithium good is carbonate or hydroxide. Meanwhile, the extraction emissions depend on the primary source of lithium and do not vary according to the final lithium good. One ton of lithium brine extracted from Chilean salt flat emits 0.091 tCO_{2e}, meanwhile, one ton of Australian spodumene emits 0.35 tCO_{2e}. Consequently, the CO₂ extraction gap corresponds to $\Delta E_{m,l-f} = 0.55 \left(\frac{tCO_2e}{t Min} \right)$.

In the lithium carbonate case, the emission gap of processing one ton of lithium carbonate from spodumene vis á vis brine is $\Delta P_{m,l-f} = 13.81 \left(\frac{tCO_2e}{t Min} \right)$. Meanwhile, the emission gap of transporting one lithium equivalent ton (LCE) contained in spodumene vis a vis lithium carbonate is $\Delta T_{m,l-f} = 0.67 \left(\frac{tCO_2e}{t Min} \right)$. In consequence, the total emission gap of producing lithium carbonate through the Leader GVC vis á vis the Follower GVC is $\Delta T_{m,l-f} = 15 \left(\frac{tCO_2e}{t Min} \right)$.

Figure 11 illustrates the total emission generated by producing lithium carbonate through the Leader GVC (China) vis á vis the Follower GVC (Chile) disaggregated at the stage level.

Figure 11: Lithium Carbonate Unit CO₂ Emissions by GVC stages for the Leader and Follower GVCs

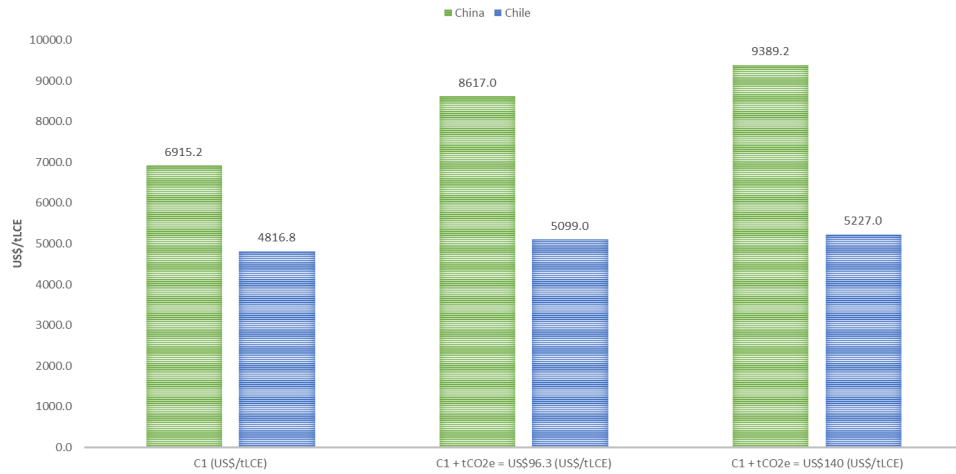


Source: Own elaboration based on own estimates.

Consequently, Chile is significantly more efficient than China at producing lithium carbonate and in environmental terms. But also it has a competitive advantage at producing lithium carbonate since the Chinese cash cost is 43.5% higher than the cash cost in Chile. Thus, when CO₂ emissions are priced and incorporated into the cash cost vectors, the cost competitiveness gaps considerably widen. For instance, as Figure 12 shows, with carbon

prices of US\$96.3/tCO₂e and US\$140/tCO₂e the cash cost gap increases up to 69.5% and 80% respectively.

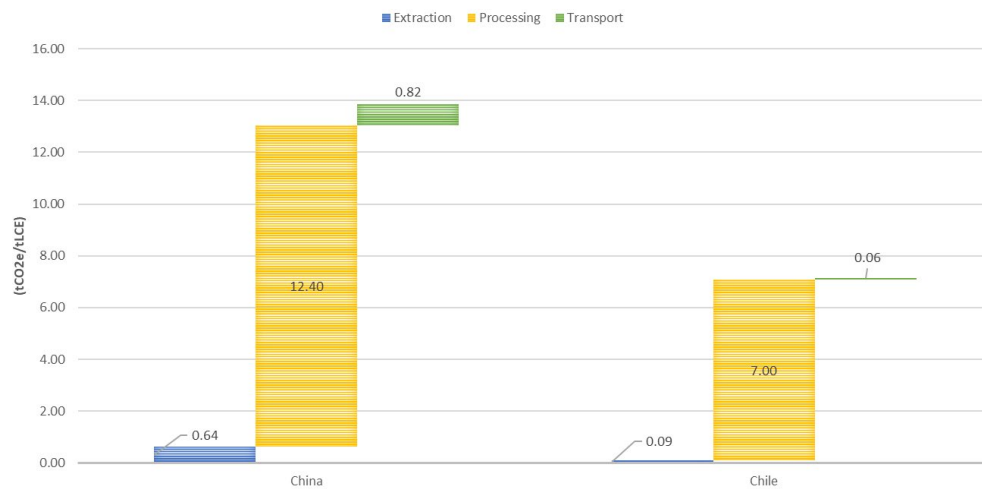
Figure 12: Cash Cost Gap of Lithium Carbonate Production by Carbon Price Scenarios



Source: Own elaboration based on own estimates.

In the lithium hydroxide case, the emission gap of processing one ton of lithium carbonate from spodumene vis á vis brine is $\Delta P_{m,l-f} = 5.4 \left(\frac{tCO_2e}{t Min} \right)$. Meanwhile, the emission gap of transporting one lithium equivalent ton (LCE) contained in spodumene vis a vis lithium carbonate is $\Delta T_{m,l-f} = 0.76 \left(\frac{tCO_2e}{t Min} \right)$. Thereby, the total emission gap of producing lithium hydroxide through the Leader GVC vis á vis the Follower GVC is $\Delta T_{m,l-f} = 6.71 \left(\frac{tCO_2e}{t Min} \right)$. Figure 13 illustrates the total emission generated by producing lithium hydroxide through the Leader GVC (China) vis á vis the Follower GVC (Chile) disaggregated at the stage level.

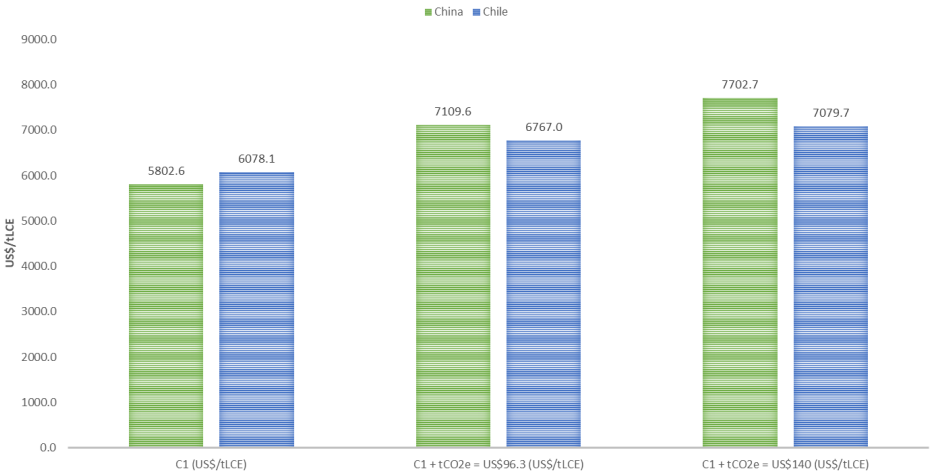
Figure 13: Lithium Hydroxide Unit CO₂ Emissions by GVC stages for the Leader and Follower GVCs



Source: Own elaboration based on own estimates.

Thereby, Chile is also more environmentally efficient than China at producing lithium hydroxide, but less than in the lithium carbonate case. On the other hand, China is more competitive than Chile since the cash cost in China is cheaper than in Chile. However, when carbon price is considered, the relative competitiveness between both GVCs changes and Chilean lithium hydroxide becomes cheaper than the Chinese. As Figure 14 shows, producing lithium hydroxide in Chile is 4.7% costlier than in China, but when a carbon price of US\$96.3/tCO₂e is incorporated into the cash costs the Chinese lithium hydroxide becomes 5.4% more expensive and with a carbon price of US\$140/tCO₂e the gap widens up to 9.3%.

Figure 14: Cash Cost Gap of Lithium Hydroxide Production by Carbon Price Scenarios



Source: Own elaboration based on own estimates.

Consequently, incorporating the value of the CO₂ emissions into the cash cost has a significant effect on the competitiveness of the refined lithium industry. In the lithium carbonate case, the current advantage of the Follower GVC (Chile) would expand up to 80%. Meanwhile, in the lithium hydroxide case, Chile would reach (catching-up) and overpass to China.

VI. Final Remarks

Based on the cost competitiveness analysis for the copper and lithium processing industries, this paper establishes that a green window of opportunity could open in the mineral processing industry. Specifically, the paper shows that pricing CO₂ emissions through the global value chain of refined minerals, in the same line as new trade and environmental regulations are establishing, would allow the Follower country (Chile) to catch up (or be close to) the leader (China). In this regard, the carbon price level and the scope of the priced emissions constitute the key variables to foster the catching-up process.

In the copper case, cash costs between China (Leader) and Chile (Follower) do not converge but the gap reduces from 232% to 25%, which is a distance reachable through technological change and productivity gains. Whilst, in the lithium case, Chile (Follower) enlarges its cost competitive advantage in producing lithium carbonate and catching-up in the lithium hydroxide industry against China. Although additional studies have to be carried on to see

if these results are extendible to other countries, looking at the composition of the CO₂ emissions of these industries and the processing costs of countries like D.R. Congo (copper), Zambia (copper) and Argentina (lithium), the catching-up process seems reachable for more lagged countries in these industries. Of course, this will depend on several factors, such as the financial flows to expand the installed capacity, which in turn depends on variables like macroeconomic stability and the conditions of the natural resources governance.

From a policy perspective, a carbon price is an efficient instrument to fix the market distortion generated by the negative externality, however, it also means an extra cost in the production of these critical minerals for the energy transition, as Figures 10, 12 and 14 show. Thereby, it establishes a trade-off in terms of net emissions. On the one hand, the carbon price changes the relative price of producing minerals between countries (GVCs), which transfers production from countries with a higher CO₂ emissions intensity to countries less intensive in CO₂ emissions. Thus, the global CO₂ emissions are reduced. On the other hand, the carbon price makes more expensive mineral production and, hence, the new technologies that intensively employ them, which has an impact on the velocity of new technology adoption. Thus, the creative destruction process slows down and fossil fuels continue operating (especially in less developed countries), which offsets the effect of production reallocation towards more environmentally efficient countries.

Additionally, environmentally more efficient countries that have committed to reaching carbon neutrality or net zero do not have an incentive to develop an industry-intensive emission even though that contributes to reducing the net global emissions. Hence, the virtuous production reallocation process is constrained by the same climate change mitigation architecture. Of course, countries will weigh economic pros and cons, but if we analyze industries with low margins, such as smelting and refining copper (Pietrobelli & Valverde, 2024), the carbon cost could be a prohibited constraint.

Consequently, the green window of opportunity in the mineral processing industry is a function of the production technology of countries that defines cost competitiveness. Nevertheless, the deeper fundamental of production costs is the international institutional framework that directly or indirectly modifies the relative prices of production.

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Annex

Table 1: Vessel Emission Factor by Type and Size of the Vessel

Type	Size	Unit	kg CO2e
Bulk carrier	200,000+ dwt	ton*km	0.0025
	100,000–199,999 dwt	ton*km	0.0030
	60,000–99,999 dwt	ton*km	0.0042
	35,000–59,999 dwt	ton*km	0.0058
	10,000–34,999 dwt	ton*km	0.0080
	0–9999 dwt	ton*km	0.0296
	Average	ton*km	0.0035
General cargo	10,000+ dwt	ton*km	0.0120
	5000–9999 dwt	ton*km	0.0160
	0–4999 dwt	ton*km	0.0141
	10,000+ dwt 100+ TEU	ton*km	0.0111
	5000–9999 dwt 100+ TEU	ton*km	0.0177
	0–4999 dwt 100+ TEU	ton*km	0.0200
	Average	ton*km	0.0132

Source: Own elaboration based on UK Government GHG Conversion Factors 2023

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