# DEVELOPMENT OF A MODEL TO STRESS-TEST THE IMPACT OF CLIMATE RISKS ON PRIMARY COPPER PRODUCTION UP TO 2050

Luis Whittle
Student number: 5387760

Supervisor: Dr. M.N. Buxton

Monitor: Dr. Ir. P. Kindt

Master of Science in Applied Earth Sciences
European Mining Course

Delft University of Technology

August, 2022

**Abstract**

The widespread concerns about climate change, as well as the major enabling factors for the transition that are required to guarantee its control, necessitate research and a tool that can provide insight into the future of copper mining.

The world's copper supply is primarily concentrated in a few producing locations: Chile, Peru, Democratic Republic of the Congo, China, and Zambia. More than 50% of the supply of this metal is produced in locations with high water stress. This is a concerning issue as the process to produce copper is particularly water-intensive. Existing physical risks such as landslides, floods, fires, and dangerous amounts of heat stress are also common and so are researched in this thesis.

Policy makers, governments, society, banks, and investors are monitoring the impact of climate risks on this industry. Therefore a tool to evaluate the risks on copper mining to allow the stakeholders to assess exposure to climate change has been developed in this thesis. To accurately analyse the future supply of copper, this tool specifically stress tests different standardized NGFS climate scenarios for years 2030 and 2050 for copper mines throughout the globe.

The simulation revealed that climate risks are a systematic risk for copper mining companies, with roughly a 50% of the supply being at high risk. Moreover, the findings suggest that this commodity is rather more vulnerable to transition risks than to physical risks, mainly due to the price of carbon. Furthermore, major producers in Chile and Peru must turn to seawater desalination and this will significantly raise operational costs. In addition, there are concerns over a possible labour migration to regions with food security issues which could jeopardize the skilled mining workforce, more research into this is required.

The findings also indicate that countries previously regarded as unattractive locations for investment, such as Zambia and the DRC, may soon rank among the major producing nations with the lowest climatic risk exposure and the lowest industry costs. However, these ratings may be offset by these countries' higher political risks.

Climate change will also affect demand. Copper is a key component of the carbon-neutral transition as numerous significant renewable technologies depend on this raw material. Furthermore, conventional copper-intensive applications such as electrical networks will also expand over the next few decades. Although investments have been pledged, it is anticipated that these will fall short of what is required to satisfy the increasing demand.

The developed model is static and reflects the issue that mines would face if they kept business as usual. This provides insights on the size of effort required by miners to overcome climate risks as well as to expose how vulnerable this commodity currently is. The model has the potential to be scaled and adapted to other commodities and to other industries. Due to its modular structure assumptions and parameters can be easily updated providing versatility and robustness.

**Acknowledgements**

I would like to thank the bank for sponsoring this project, specifically Peter Kindt and Cilia Ruinen for their commitment and their willingness to share their experience. I also want to thank the helpful and experienced feedback from my TU Delft thesis supervisor, Mike Buxton, who guided me throughout the whole process. Additionally, I would also show my gratitude to Masoud Soleymani who participated in several meetings and provided his interesting feedback. Finally, I would like to express my gratitude to my peer Anna Broughton that reviewed my thesis and provided me valuable feedback.

# List of acronyms

**AMD** Acid Mine Drainage

**BFS** Bankable Feasibility Study

**CODELCO** Corporación Nacional del Cobre (National Copper Corporation)

**CACB** Central African Copper Belt

**CAPEX** Capital Expenditures

**CDR** Carbon Dioxide Removal

**CRISK** Climate risk

**DRC** Democratic Republic of Congo

**EAD** Exposure At Default

**EBITDA** Earnings Before Interests Taxes Depreciation and Amortization

**EV** Electric Vehicle

**EU** European Union

**FS** Feasibility Study

**GOR** Gross Overriding Royalty

**HSE** Health, Safety, and Environment

**HSI** Heat Stress Index

**IOCG** Iron Oxide Copper-Gold

**IPCC** Intergovernmental Panel on Climate Change

**IPCC** In-Pit Crushing and Conveyors

**IPO** Initial Public Offering

**GDP** Gross Domestic Product

**GHG** Greenhouse Gas Emissions

**LIBOR** London Interbank Offered Rate

**LOM** Life Of Mine

**LPM** Loan Portfolio Management

**LSI** Landslides Index

**LTD** Long Term Debt

**NGFS** Network for Greening the Financial System

**NPV** Net Present Value

**NSR** Net Smelter Return

**NPI** Net Profits Interest Royalty

**OPEX** Oprational Expenditures

**SERNAGEOMIN** Servicio Nacional De Geología y Minería (Nacional Service of Geology and Mining)

**SONAMI** Sociedad Nacional de Minería (Nacional Society of Mining

**PRISK** Physical Risk

**ROM** Run Of Mine

**SEDEX** SEdimentary Exhalative

**SCRV** Sedimentary Controlled Replacement and Vein

**SEO** Secondary Equity Offering

**SPV** Special Purpose Vehicle

**SRISK** Systemic Risk

**SX-EW** Solvent Extraction and Electrowinning

**TC/RC** Treatment Charge (TC) and Refining Charge (RC)

**VMS** Volcanic Massive Sulphide

**UN** United Nationsk

**WFI** Wildfire Index

**WSI** Water Stress Index

# Contents

# List of Figures

# Chapter 1

# Introduction

## 1.1 Research context

Climate change is a phenomenon that is becoming increasingly apparent, extreme weather and extinction of wildlife are among the multiple consequences that experts conclude may be irreversible at this point.

During the climate change conference of COP21, 196 parties entered a legally binding international treaty (Paris Agreement) on climate change to take immediate action slowing down global warming (UN, 2015). Targets and deadlines were outlined creating disparity as countries that cannot adequately reduce their greenhouse gas emissions (GHG), would result in challenging interventions from governments aiming to achieve the goals.

Recently, the UN (2022) acknowledged that forecasts regarding global warming have been underestimated and described the current situation as a "code red for humanity". This has been based on the warnings disclosed in the last report published earlier this year from the Intergovernmental Panel on Climate Change (IPCC). Experts further stress that limiting climate change will require a substantial reduction of GHG emissions than previously expected.

Additionally, according to Delevingne et al. (2020) mining accounts for approximately 5 to 7 percent of global GHG generation, however its existence is necessary in providing critical raw materials needed, such as copper, for the development of energy transition. Banks that finance this industry must oversee their exposure of their balance sheets to these uncertainties and enhance the financing of a green agenda. Thus, the development of a metric to assess these issues is crucial for correct management.

## 1.2 Problem statement

During early 2021, the Basel Committee on Banking Supervision (BCBS) presented the results of their research that aimed to detect the main risk drivers and transmission channels as well as to discuss the state of art of the methodologies that banks have available or are currently being developed. In the same way, the bank has been developing new assessment processes that can allow the bank to adjust governance structure, policies and risk appetite based on climate related metrics and goals for each industry (BIS, 2021).

As previously mentioned, in the upcoming decades climate change will produce wide range of economic, business, and social risks; hence quantifying them is essential. Presently, measuring the effects of climate risk is a great challenge especially in complex industries like mining in which multiple variables play a role. For this reason, climate risks quantification in mining is still a cutting-edge concept that is far from being fully understood and developed, yet a crucial capability that needs to be enabled urgently given that mining companies and related institutions are under progressively more political, social, and regulatory pressure.

Furthermore, climate risks are deemed as more complicated to estimate than traditional financial risks as the former in some cases lacks data in comparison to the plenty and reliable historical data for the latter. However, the challenge remains to develop an approach that is able to assess the specific climatic risk exposure of primary copper producers, thus a climate risk stress-testing will be carried out in this study.

For the specific case of mining, financial institutions are interested in physical and transition risks that climate and related new policies and regulations will have in their current operations and ultimately the current and future cash flows of the mines that are currently being financed by them. In order to know this, it is necessary to align a methodology on climate scenarios and analyze clients case by case, e.g., their $CO_2$ emissions, sustainability of their processes and assets, their road map among other factors. Hence, developing this tool will enable financial institutions to allocate these risks and overview their portfolio of clients with a sustainable perspective. Moreover, this study will also help governments and regulatory institutions to assess current operating companies and their performance under different climate scenarios to monitor more efficiently on the most exposed ones.

## 1.3 Hypothesis

The hypothesis for this work is then the following:

*It is possible to develop an assessment tool to measure climate risks in primary copper producers as well as to stress-test their performance and consequent producing costs under different climate scenarios till 2050.*

Multiple factors will be part of the evaluator that will stress-test each primary copper mine and will provide an assessment of the risks by modelling blocks and interlinkages as displayed in Figure 1.1.

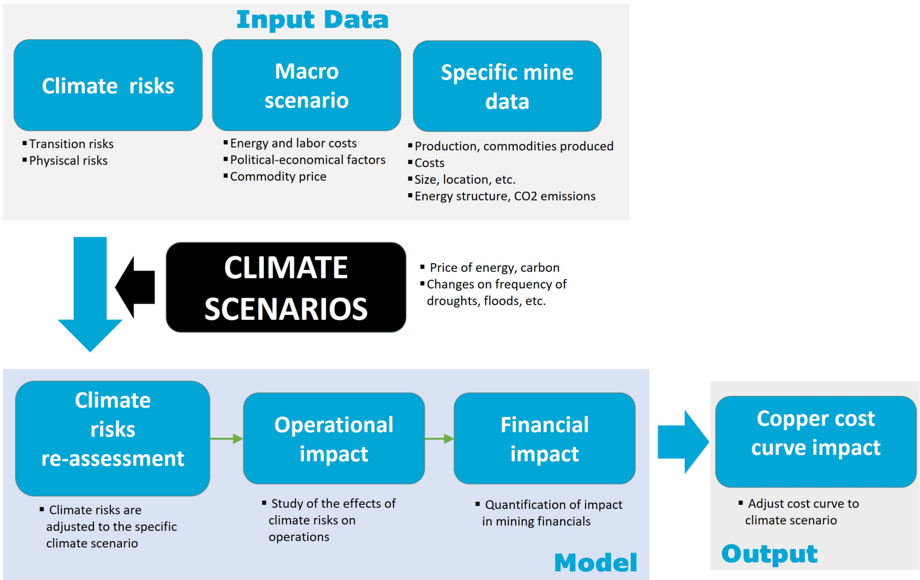


Figure 1.1: Model initial approach. Own elaboration.

## 1.4 Goals and research

The aim of this thesis is to study copper mining's climate risks as well as their effects in the performance over this companies through stress-testing. To achieve this, the approach will be to study the available literature to comprehend the topic and the state of art of climate risk stress-testing. The data to be used in this thesis is reviewed in more detail later in this chapter and it comprise CRU and S&P mine companies technical database, NGFS climate scenario data base and open sources of data.

From the previous sections three research questions and four objectives were defined:

1. What will be the impact of climate risks on copper mining operations?
2. What is the outlook for copper producers under different climate scenarios?
3. How would climate change affect mines' finances and copper supply under different climate scenarios?

From the previous research questions, four objectives were defined:

**Objective 1: Define what data are required**

One of the first challenges will be to find and determine valuable usable data to carry out this thesis. As mentioned previously, sources and their native format are very diverse, thus it will be needed to extract, format, merge and store this data in order to use it for the following blocks. Since there are overall limitations in relation to the linkage of the available data to transition and physical risks, simplifying assumptions are likely to be made in order to fill potential gaps.

**Objective 2: Prepare climate scenarios for the model**

A well-designed stress-testing scenario, or multiple scenarios, must reflect effectively both physical and transition risks. The combination of the input data shown in Figure 1.1 will determine the scenario for the different mines to be evaluated, this will be turned into key macroeconomic variables and later into potential financial losses. Moreover, long time horizons are likely to be used as it is the expected time that risks factors will materialize, on the other hand too long horizons also increase the uncertainty of the assessment. Hence, for a proper stress-testing, a well selected variety of scenarios should be chosen as well as time horizons of the evaluation and proper assumptions.

**Objective 3: Creating an evaluator to process and simulate this scenario**

Once providing a suitable scenario for the evaluator, the following block will need to quantify the impact of each scenario for each mine. This will consider macroeconomic impacts, geographies, projected cashcosts, etc. All these components will be computed and will provide the impact for the each mine's cash-costs as well as the whole copper supply cost curve.

**Objective 4: Assessing the results and consequences of the evaluator**

A large number of scenarios are required to reflect the high degree of variability around climate risks, nevertheless this also provides a broader scale of outcomes in relation to the referenced metric. This wide range will make possible to the reader to better understand the implications, vulnerabilities, physical and transition risk concentrations within primary copper producers.

## 1.5 Sample, methods and approach to analysis

### 1.5.1 Copper mining data

The data regarding the copper deposits and reserves were extracted from the database of Singer (2017). This database included a total of 2300 copper deposits, indicating geology type, known resources in all copper-bearing deposits to document known sources by type of deposit, geology, by location, and by grades and tonnages of ore and metal. The author gathered the data from primarily documented compilations of different kinds of deposits that contain copper.

The overall mine data corresponds to the database linkage of S&P Global and CRU for years 2021, 2030, and 2050. These databases provide data about their finances, coordinates, production, among others. Both are internationally renown firms that offer independent, reliable commodity news, market analysis, prices and consulting across several industries including mining and metals.

In the case of S&P Global, the data obtained includes general information on copper-producing mines, such as their name, location, yearly output, owners and their respective share, and their cash costs. The latter are classified in Labour, Energy, Reagents, Mining, Other Costs, Royalties, and TCRC+Shipment, all of them in cents per pound of metallic copper. This database provides the option to filter only primary copper producers, which is based on the commodity that composes the greater part of the revenues. After applying this filter a data base with a total of 279 mines in 2021 with a total production of 16.494 million tonnes, 218 in 2030 with a total production of 17.293 million tonnes, and finally 124 in 2050 with a total production of 11.285 million tonnes.

CRU's database contains 279 mines in 2021 with a total production of 21.866 million tonnes of copper, 284 mines in 2030 with a total output of 27.076 million tonnes, and 142 mines in 2050 with a total output of 18.182 million tonnes. This database contains basic mine data such as name, location, owner, yearly copper output, production expenses, and $CO_2$ generation of each mine, as well as its breakdown by process and $CO_2$ scope. This breakdown by process includes: mining, processing, downstream processing, transportation and shipping, and maritime freight to the market. Since CRU provides the $CO_2$ output of each mine but does not allow for filtering by primary copper producers, it was required to integrate the SP database, with the CRU database.

Note that the dataset's forecasted copper output seems to be decreasing over time. However, this is not realistic since the data only include present operations and future incoming known projects in the medium term, but the amount of new projects from 2030-2050 is uncertain for a 2050 projection, hence the data has this limitation.

### 1.5.2 Climate data

The baseline of physical risks was acquired by open sources such as NASA and the World Resources Institute. Given the massive nature of the data, it was processed and simplified exclusively for the provinces where the primary copper producers are located. This allowed to speed up the computation of the data significantly. With this data, pre-established indices were used, as well as indices were created based on the typical physical risks faced by copper mines.

### Heat stress

Cong (2021) provides a dataset through his study that can accurately reflect typical extreme temperatures and heat wave events. The related study created a global apparent temperature and heat wave (GATHW) toolbox based on the Climate Data Store (CDS) online platform using ERA5 hourly data on single levels of 2 m temperature, wind speed, dewpoint temperature, and solar radiation. The dataset of this study contains data from 2006 to 2020 and it was acquired from China's National Qinghai Tibet Plateau Scientific Data Centre (https://www.doi.org/10.5281/zenodo.4764325). The National Tibetan Plateau Data Center (TPDC) is one of 20 national data centers established in 2019 by the People's Republic of China's Ministries of Science and Technology and Finance. The TPDC is hosted by the Chinese Academy of Sciences' Institute of Tibetan Plateau Research (ITPCAS), with assistance from Lanzhou University, Beijing Normal University, and the Chinese Academy of Sciences' Computer Network Information Center.

### Water stress and flooding

The dataset used to quantify water stress and flooding was acquired from Gassert et al. (2013). This database was constructed through study review, public domain data sources, and expert review of the data. The hydrological catchments were based on the Global Drainage Basin Database. The Wold Resources Institute (WRI) is a global research organization that engages with governments, companies, international institutions, and civil society organizations to produce practical solutions that enhance people's lives while also ensuring the survival of nature. We focus our efforts on seven global issues: food, forests, water, energy, climate, the ocean, and cities.

### Landslides

Data regarding landslides was acquired from Kirschbaum (2018). The Global Landslide Catalog (GLC) was created by NASA with the objective of detecting rainfall-triggered landslide occurrences worldwide, regardless of magnitude, impact, or location. The GLC takes into consideration all forms of mass movements caused by rainfall, whether reported in the media, catastrophe databases, scientific papers, or other sources. The GLC has been collected by NASA Goddard Space Flight Center since 2007.

### Wildfires

A Wildfire databank was obtained from NASA's Global Fire Atlas (Andela et al., 2019). This is a global dataset that monitors the daily dynamics of individual fires to determine ignition timing and location, fire size, duration, daily expansion, fire line length, pace, and spread direction. The Global Fire Atlas method and estimated day of burn information at 500-m resolution from the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 MCD64A1 burnt area product were used to construct these individual fire characteristics. Over the 2003-2016 research period, the program recognized 13.3 million individual fires (¿=21 hectares or 0.21 km2; the area of one MODIS pixel).

### Physical Indices Normalization

For this study, four main climate physical indexes will be employed to measure actual physical risks, some of them are completely unmodified from their published form, while the rest have been adapted from external sources. However, in order to perform a comparative analysis, all of these indexes have been normalized into a scale of 0-5.

- **Water stress index:** The source defines this index as the total annual water withdrawals (municipal, industrial, and agricultural) as a percentage of total yearly available flow. Higher levels suggest therefore greater user competition. When computing aggregated scores, arid areas with minimal water use are depicted in gray yet rated as high stress. (2010) water withdrawals divided by mean available blue water (1950–2008). Arid and low water usage areas have accessible blue water and water withdrawals of less than 0.03 and 0.012 m/m2 respectively.
- **Flooding index:** The source describes it as the number of floods recorded from 1985 to 2011. Number of flood occurrences (1985-2011). Flood counts were calculated by intersecting hydrological units with estimated flood extent polygons.
- **Heat stress index:** The amount of perspiration necessary in proportion to the maximum amount of fluid that the average individual can through evaporation remove from their body to cool it down is known as the heat stress index. Humans are susceptible to heat stress when the heat index is high, which can result in extremely hazardous situations when people individuals could actually pass away from overheating and improper self-cooling. When the heat stress index is high, excessive exposure can cause severe dehydration and even death. This measure is intended to forecast the likelihood that an average person will experience physiological heat stress. This index was normalized from the source.
- **Landslides index:** Considering that landslides have no index in the literature. An index was built and then normalized using information from public sources to describe the likelihood of the risk occurring as it follows:
  $LSI = \sum events$
- **Wildfire index:** Similarly to the above, there was not an wildfire index in the literature. Due to this, an index was described and then normalized using parameters as well. However, in order to keep all parameters in the same order of magnitude and avoid over weighting one of them, logarithms were applied:
  $WFI = perimeter \cdot duration \cdot speed \cdot \log(frequency)$

### 1.5.3 Climate Scenarios data

The data regarding climate scenarios was obtained from Network for Greening the Financial System's (NGFS) Climate Impact Explorer tool (NGFS, 2022). This tool gives users access to the global raw data down to the province level of different parameters (further described in Appendix) and their values according to the severity of climate change effects at various degrees of global warming, beginning with 1.5°C, the Paris Agreement's limit. NGFS scenarios are based on input data and analysis from the 2018 Intergovernmental Panel on Climate Change (IPCC) Special 1.5 degree climate report. The NGFS has modified them to assist central banks and regulators in exploring the potential effects on the economy and financial system in a standardized manner. On the other hand, the IPCC is the United Nations body created by the World Meteorological Organization (WMO) for assessing the science related to climate change. This institution provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation.

### 1.5.4 Miscellaneous data

#### Boundary Polygons

To measure the climate indices at the provincial level, a database was obtained from Krause (2021). This database contains the global borders of all provinces according to ISO 3166-1/2 in. shp format. In this study, these polygons were utilized to categorize mines at the provincial level.

#### Case studies

Case studies concerning climate risks and operational disruption were obtained from diverse public domain sources. These case studies describe the relationship between both and ultimately the financial consequences under each climate scenario.

### 1.5.5 Analysis approach

This thesis is divided in 5 different chapters that follow the next steps:
**Step 1 - Data analysis of current state of global production:**
The database utilized for this study is examined in this chapter. Additionally, copper mining is described, including how it is done, who the key players are, supply and demand, as well as the inherent political hazards of this commodity.
**Step 2 - Study on copper mining financials:**
This chapter presents the background of how a mining project is financed and which are the main costs that include copper mining and its corresponding drivers.
**Step 3: Study of climate risks and scenarios:**
In order to conduct case studies for each location, the goal of this chapter is to characterize the climatic risks impacting copper mining through the subdivision of geographic zones. In addition, climate scenarios, their assumptions and limitations are explained.
**Step 4: Aligning copper mining with climate scenarios:**
The convergence of all the previous chapters is carried out in this chapter, where

the climatic risks studied are corrected from each scenario and then applied to the copper mines of the database used to finally see the financial implications for each case.

**Step 5: Results discussion:**

Finally, these results are discussed, providing the implications for each case and the conclusions of this study.

# Chapter 2

# Overview of copper mining

**Introduction**

Copper is classified by ICSG (2021) as a noble metal, which means that it does not pollute, oxidize, or degrade and can be recycled indefinitely. This metal is coveted in the industry due to its various properties. These include high electrical conductivity, degree of thermal conductivity, malleability, corrosion resistance, metal alloy capacity and deformation capacity. Additionally, copper maintains its properties indefinitely in recycling and has bactericidal properties. These features make this metal a highly sought-after commodity in emerging and high-impact industries, for example, because of its high thermal and electrical conductivity and its zero magnetism, copper is ideal for the transmission of data, sound and images in the telecommunications sector.

According to LME (2022), this metal is formally traded through the London Metals Exchange in dollars and in batches of 25 tons, through the New York Mercantile Exchange, which deals based on batches of 25,000 pounds quoted in cents, and finally the Shanghai Metals Exchange, where it is traded in batches of five tons quoted in Renminbi.

## 2.1 Geography

The deposits of copper ores include several types that differ in the geological conditions of their occurrence or the mineralogical and petrological properties of the ores. The main deposit types have been sorted by (Krzak, 2021) and include the following in order of relevance: (1) Porphyry (2) Sediment-hosted (Kupferschiefer-type) (3) Volcanogenic massive sulphide (VMS) (4) Magmatic sulphide deposits (5) Sedimentary exhalative (SEDEX) (6) Epithermal (7) Copper skarns (metasomatic) (8) Vein-style deposits (polymetallic veins) (9) Iron oxide copper-gold (IOCG) (10) Supergene.

Geographical allocation, geological setting, origin and mineral composition of sediments reveal various geological overlays, including vast copper-containing areas. The most well-known are the Pacific Ore Belt (Andescordillera, North America), Kazakhstan's Altide, Iberian Peninsula, Kupfersiefer (Central Europe), Central African Copper, Gawler Craton (Australia), and others (see fig. 2.5). The worldwide distribution of copper deposits is unequal. In respect to continents, the Americas and Africa are the most dense (Krzak, 2021).

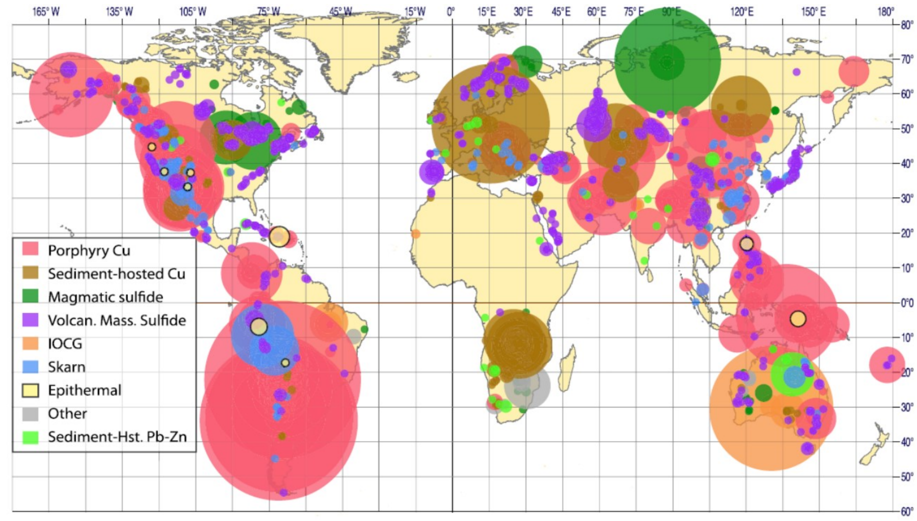


Figure 2.1: Global distribution of copper content by deposit type. Sizes of circles equal relative amount of copper in each deposit. From Singer (2017).

Moreover, copper is a metal that can be mainly found in large quantities in very specific areas around the globe. Clear evidence of this is that 92% of the total reserves are hosted by the largest 20% producers (fig. 2.2).

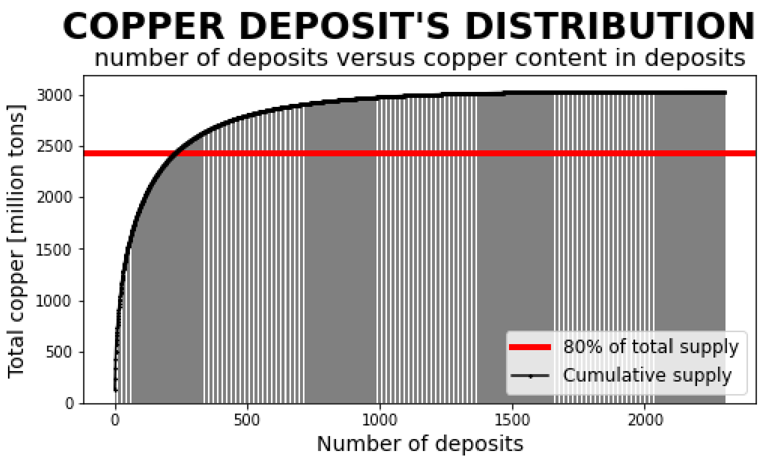


Figure 2.2: Size distribution of copper deposits. Own elaboration adjusted from Singer (2017).

Furthermore, from the discovered copper deposits, 75% of deposits are Porphyry, followed by the Sediment-hosted (11%), then Volcanic massive sulphides or VMS (3%), and then fragmented into diversified types of deposits (fig. 2.3). A further analysis over fig. 2.3 will be carried out in the next subchapter.

According to ICSG (2021), only two types of deposits account for the 80% of undiscovered reserves in the world.

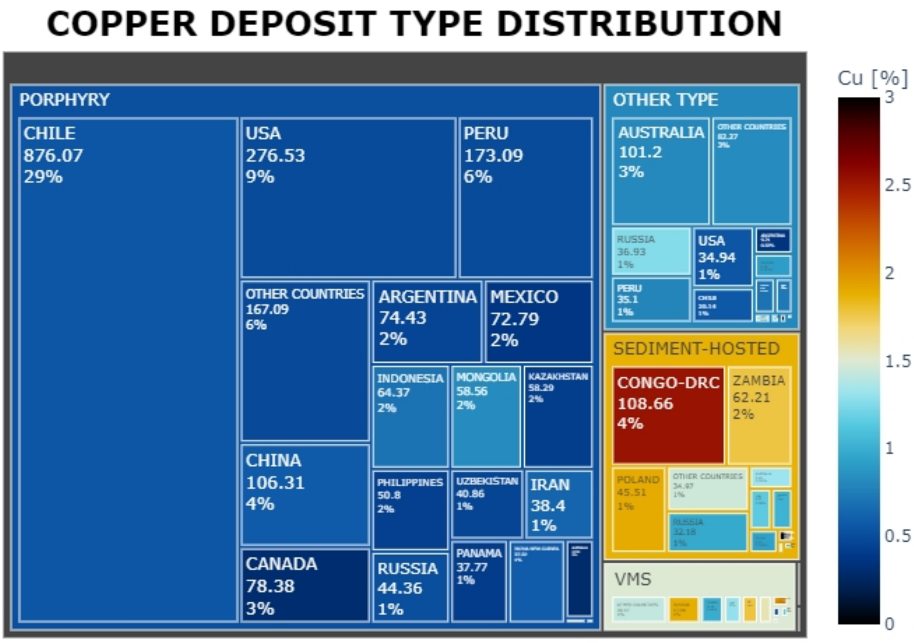


Figure 2.3: Copper discovered reserves distribution according to deposit type, grade and estimated total million tonnes of copper. Own elaboration adjusted from Singer (2017).

Porphyry deposits are usually found around volcanic regions for which its vast majority has been deposited in sulphidic minerals. In particular, the pacific ring of fire is a region that extends from the pacific coasts of the American, Asian, and Oceanic continents; and it is characterized due to its highly active volcanic and tectonic activity. In this area, the boundaries of the tectonic plates run along the Pacific basin (Figure 2.4). These regions contain massive amount of Porphyry Copper and can be divided into five main geographic areas (John et al., 2010):

(1) Andes
(2) North American Cordillera
(3) East Asian
(4) Southwest Pacific
(5) Tasman.

On the other hand, roughly 20% of copper can be found in sediment-hosted stratabound copper deposits where copper is part of layers of sedimentary rocks (ICSG, 2021). According to Taylor et al. (2010), there are three main sedimentary basins: the Paleoproterozoic Kodaro-Udokan in Siberia, the Neoproterozoic Katangan in central Africa, and the Permian basin of central Europe.

The Central African Copper Belt, otherwise known as CACB, has about half of the copper known to be in sediments (already produced and discovered resources). Furthermore, much of the copper produced in Africa and roughly 7% of the world production comes from the CACB. This region is within the Neoproterozoic Katanga Basin in the Southern Democratic Republic of the Congo (DRC) and Zambia. CACB copper is mined from deposits in the Kolwezi and

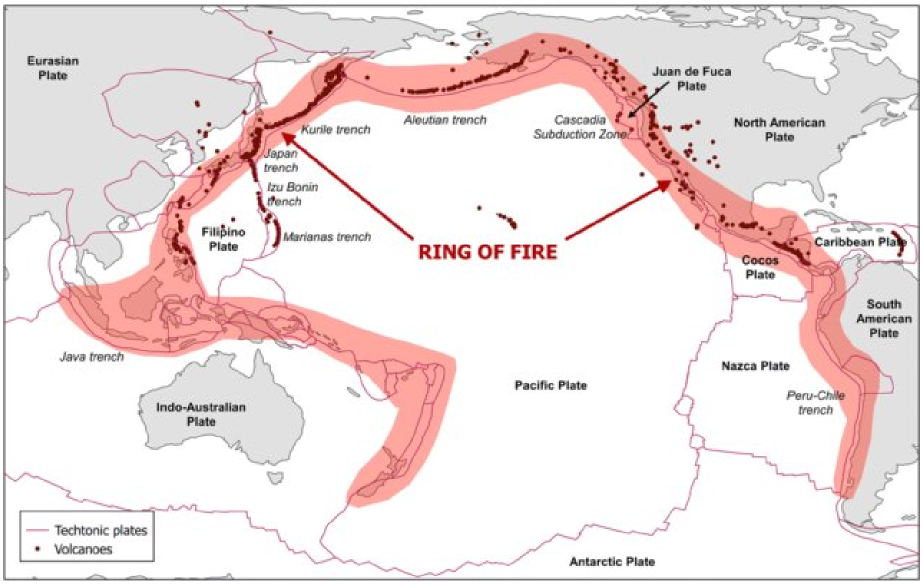


Figure 2.4: Subduction zones in the Pacific ocean—the Ring of Fire or the circum-Pacific belt. From Cheff and Palermo (2018).

Tenge Fungurume districts of the Democratic Republic of the Congo, and the Konkola Musoshi and Nchanga Chingola districts of Zambia. Sediment-hosted structurally controlled replacement and vein (SCRV) copper deposits e.g., the giant Kansansi deposit in Zambia, have become recently important exploration targets in the CACB region (Taylor et al., 2010).

The largest copper ore deposits in Europe are known from occurrences in the overlying Zechstein platform formations (Central Europe) and include various deposit types: sediment-hosted, porphyry, IOCG, and VMS (Oszczepalski et al., 2019).

**Focus of this study**

For this work, exclusively main copper producer deposits-mines were considered. The rationale for this is to be able to isolate secondary copper producers, since in most cases this does not yield a comparative analysis. Likewise, the locality of the primary producers is generally clustered in particular areas, which also allows the study to have less variability when analyzing the physical effects of climatic risks. The copper deposits that are considered primary producers are shown below:

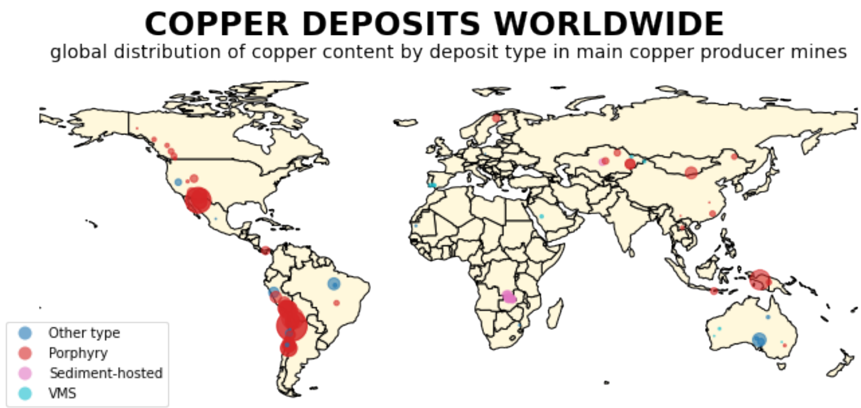


Figure 2.5: Global distribution of copper content by deposit type for primary producers. Sizes of circles equal relative amount of copper in each deposit, colors refers to different deposit types. Own elaboration based on Singer (2017) and S&P Global database.

S&P Global's criteria for defining primary producers in its database is based on the revenues of each asset. Therefore, the commodity that contributes the most to total revenues on a sustained basis over time is then considered the primary commodity for that particular mine. Note that this is dynamic and can change over time due to variability in metal prices.

## 2.2 Geology

Each type of deposit is characterized by individual qualitative and quantitative characteristics. Apart from geological features, deposits resources and ore quality are determined by economic factors and individual balance criteria (Oszczepalski et al., 2019).

The geology of copper is highly varied with distinctive features and may be found in a variety of minerals that are located in deposits big enough to mine. Azurite, malachite, chalcocite, acantite, chalcopyrite, and bornite are some of these minerals. Nevertheless, chalcopyrite is the primary source of copper.

As a complement to the previously presented Figure 2.3, Figure 2.6 displays the statistic distribution of the deposits in terms of location, grade, and size. At a first glance, it seems an inverse proportion can be inferred between the grade and the deposit size, which in other words means the bigger the deposits, the lower the grade, and viceversa.

From both figures, it is clear that porphyries represent the primary deposits from which copper can be found in most of the top 20 countries. These kind of deposits are known for their massive volume yet low grades. On the other hand, sediment-hosted copper is the following main deposit which is characterized because of their moderate size with higher grades and specific locations where it occurs (Congo, Zambia and Poland). Lastly, volcanic massive sulphides deposits have smaller sized deposits with moderate mean grades, nonetheless with a considerable dispersion, hence ranging from very low to very high.

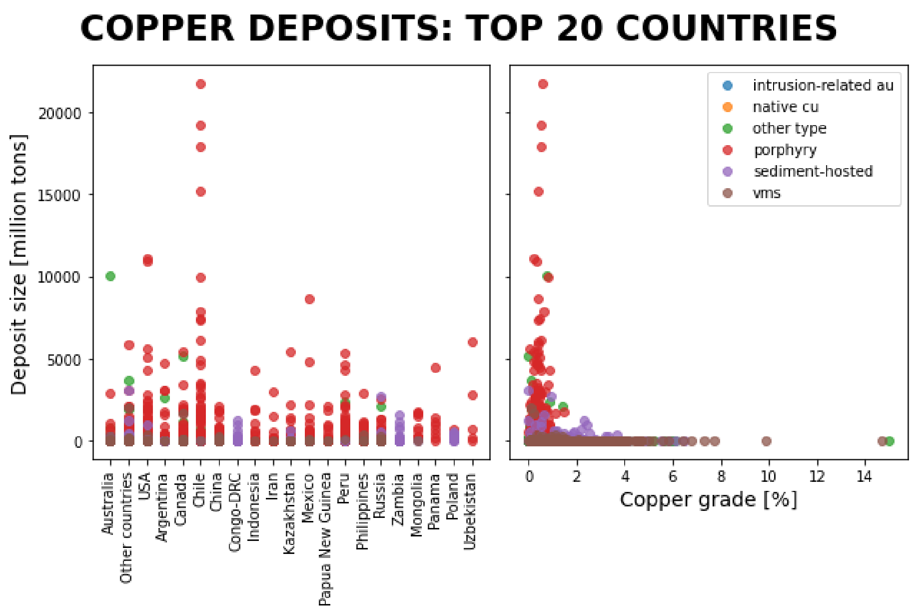


Figure 2.6: (1) Relationship of copper deposit in top twenty countries type and size, (2) Copper deposit type, size and grade relation. Own elaboration adjusted from Singer (2017).

From the previous sub-chapter the geology of two mentioned main deposit styles i.e.: Porphyry and Hosted-sediment copper, cover more than the 80% of copper world reserves, thus this sub-chapter will deep dive in the geology of them.

### 2.2.1 Copper porphyries

These deposits are known for their large size in magmatic belts around the globe (see fig 2.7). Porphyry copper deposits, also known as PCDs, are the world's most important source of copper and other metals such as molybdenum, gold, and silver that can be found in lower proportions. Aditionally, these deposits are characterized by their massive amount of ore tonnages, in where copper is dispersed through large volumes of hydrothermally altered rock (veins and breccias), yet with lower grades i.e., often ranging from 0.3 to 2 percent copper. Even though these deposits contain low-grade ores, their large size and often long life of mine (LOM) accounts for relevant socio-economical impacts to the nearby communities (John et al., 2010).

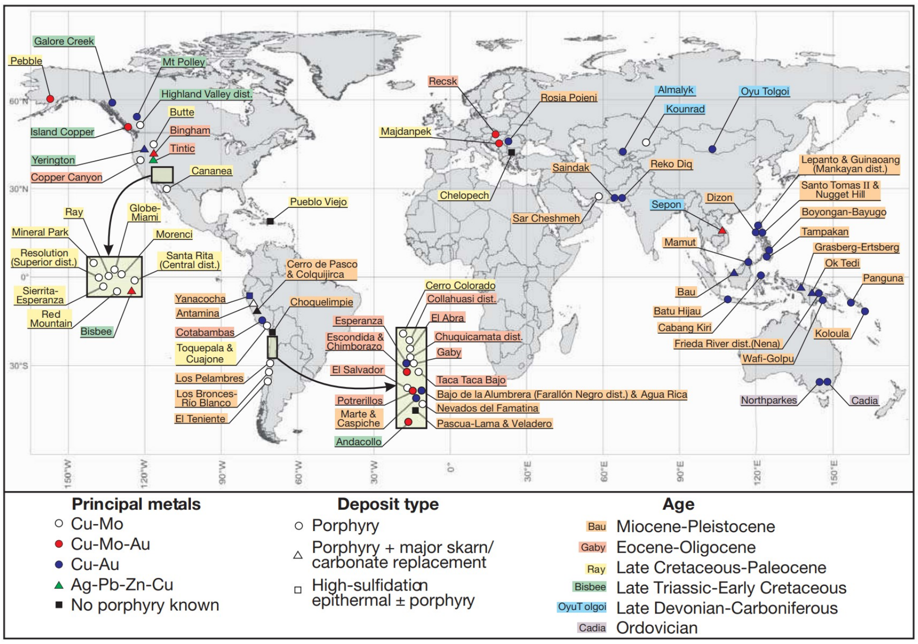


Figure 2.7: Worldwide locations, deposit types, contained metals and age of porphyry Cu systems. From Sillitoe (2009).

In line with Frei (2005), a copper porphyry deposit undergoes different environmental processes, or weathering, that allows them to classify different zones within them. These will contain various minerals which will be processed differently afterwards (see fig 2.8). The first is the oxidized zone which is the closest to surface. In this zone, the acidic ground water and oxygen react with copper sulphides resulting in rusty-stained bleached ores called copper oxides. The second is called supergene, and describe the so called secondary sulphides. The supergene zone is a near-surface process characterized by its low temperature and pressure, and absence of oxygen as it occurs below the water level. The copper-enriched acid solution from the oxidized zone reacts with the sulfates and produces the enrichment of these minerals. The last zone is called hypogene and gives place to primary sulphides (Sillitoe, 2009). This region hosts the minerals deep in the earth below the water level, for which this region has not been weathered nor enriched. According to (John et al., 2010), because of enrichment, supergene copper sulphide grades are normally greater than hypogene copper grades.

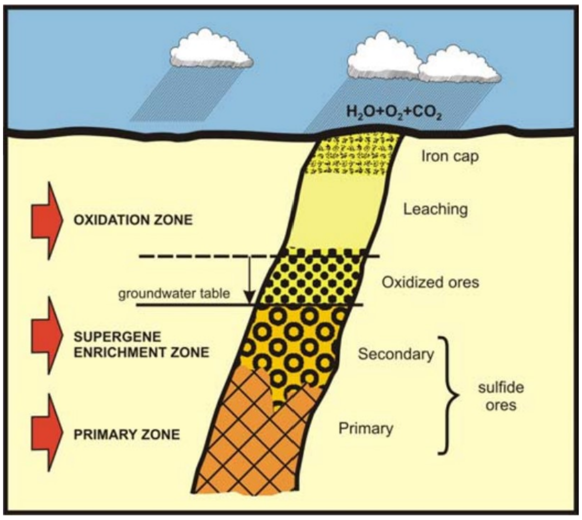


Figure 2.8: Development of a copper deposit. From Frei (2005)

Although PCDs are mined primarily to extract copper, John et al. (2010) mentions the diverse types of minerals that can be extracted, such as:

- Skarns (including copper, iron, gold, zinc types)
- Polymetallic replacement (silver, lead, zinc, copper, gold)
- Polymetallic veins (gold, silver, copper, lead, zinc, manganese, arsenic)
- Distal disseminated gold-silver (gold, silver)
- Epithermal vein (intermediate/low sulphidation goldsilver)
- High sulphidation epithermal (gold, silver, copper, arsenic

However, according to Sillitoe (2009), the three most important metals by value worldwide in copper porphyries are Cu (copper), Mo (molybdenum) and Au (gold).

### 2.2.2 Sediment-hosted copper

As analysed in Section 2.2, sediment-hosted copper deposits present smaller size of reserves, but with overall higher grades. Ore is in this case stratabound i.e, confined to particular horizontal layers inside a sedimentary basin. Their formation occur after the host's sediments have deposited. (Cox et al., 2007) notes two main rock types, low and high-energy. The former is composed primarily by calcareous or dolomitic siltstones, shales, and carbonate rocks of marine or lacustrine origin, whereas the latter by sandstones, arkoses, and conglomerates of continental origin.

Arndt et al. (2017) explains how earlier hypotheses led to think that copper settled syngenetically from seawater but was proven wrong later. The last studies have then shown that in fact copper was deposited once the sedimentary rock was already deposited. Furthermore, oxidised basinal brines with the salinity obtained from evaporation of saltwater and/or dissolution of evaporites are assumed to have leached copper from underlying volcanic rocks, arkosic deposits, and the basement.

Taylor et al. (2010) describes the formation of these deposits consists in the mixing of two fluids into a permeable host rock (sedimentary or rarely volcanic). The first fluid is a copper concentrated oxidized brine contained in a chloride complex, and the second is a reduced fluid. Hassanpour and Senemari (2015) notes that the first fluid as the one responsible to mobilize copper, and the second being the one in charge to destabilize the complex ability of the first fluid, and precipitate the copper into the host rock (see fig. 2.9)

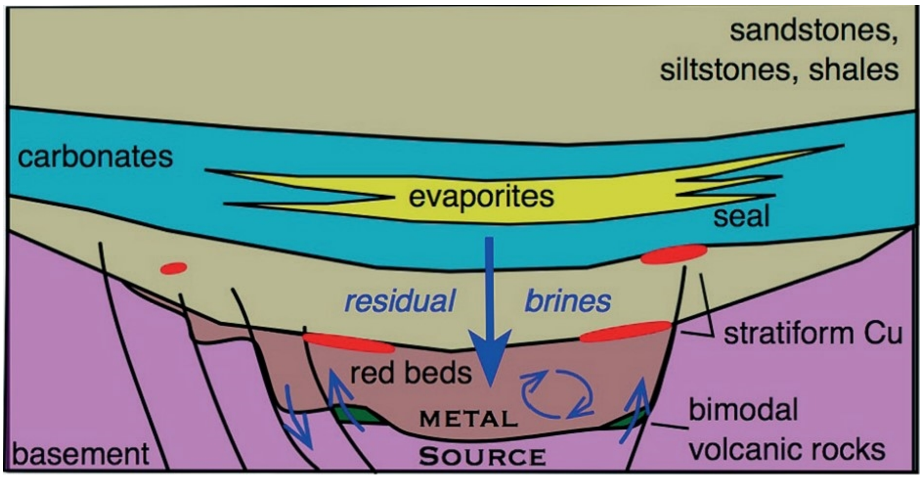


Figure 2.9: Development of a sediment-hosted copper deposit. From Arndt et al. (2017)

## 2.3 Copper mining

### 2.3.1 Mining and processing

Depending on the geology of the deposit, mining methods can differ. Arndt et al. (2017) has described the particularities of both copper porphyries and sediment-hosted deposits:

#### Porphyries deposits mining

Copper porphyry deposits account for about 65% of the world's annual production of this commodity. These deposits are linked with porphyric intrusions and consist of large masses of rock, generally with low grade Cu. Since the volume and grade have this relationship, most of these mines are exploited through open-pits or underground through block caving. Moreover, given the big scale of production, efficient big size equipment i.e.: shovels, trucks, conveyor belts, crushers, and grinding circuits, are needed to handle the mined material.

In the case of primary sulphides, these are commonly mined through open pit or underground, followed by grinding and flotation. However, it is noted that mining via open pit is considerably disadvantageous in the long run as pit become larger, thus hauling costs and waste increase if compared to underground, yet the latter requires high initial capital. Codelco Andina Mine is a good example of primary sulphides mining (Figure 2.10).

Figure 2.10: Codelco Andina copper mine in Chile. Courtesy from Codelco (2022a)

As explained previously in 2.2, porphyry deposits that have experienced weathering will have copper oxides and potentially supergene enrichment blankets where chalcocite will be likely predominant. Due to weathering, copper has traveled from the original porphyry deposits and has been settled into the surface gravels. Given these circumstances, copper oxides are commonly mined through shallow open-pit mining. Figure 2.11 shows Codelco Gabriela Mistral Mine mining oxidized ores (colored in blue) from the surface.

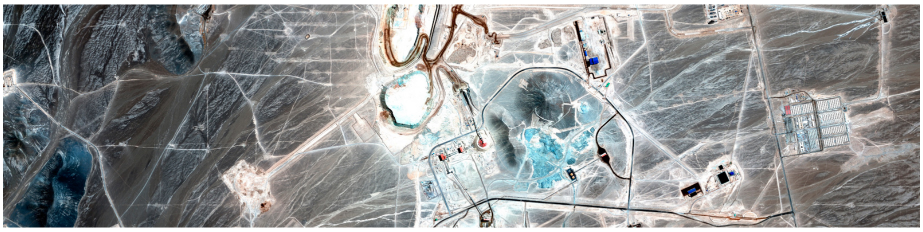

Figure 2.11: Codelco Gabriela Mistral copper mine in Chile. Courtesy from Codelco (2022b).

**Sediment-hosted deposits mining**

Sediment-hosted deposits contain high grade but thin layers of sedimentary ores placed between oxidized and reduced rocks. Normally these layers are flat with little or no dip, hence often mined through shallow open pits in case of near to surface ores. However, shallow mines are hard to mine in an efficient way, hence most of the production coming from these type of deposits are produced through underground mining, allowing to mine the thin mineralised layers with some degree of dilution from the barren rocks that lay above the ore. The ore is then typically crushed underground and then handled to the surface through shafts. These ores are also commonly just grinded and floated to be sold as concentrates afterwards; hydro-metallurgical treatments rarely take place at sites. Kinsevere copper mine displayed in Figure 2.12 shows the usual shallowness of a sediment-hosted copper mine.

Figure 2.12: Kinsevere copper mine in DRC. Courtesy from SRK (2022).

### Processing

Processing allows to increase the copper content of the ore since the ores that are mined are of low grade. As reviewed previously, copper can be found in sulphide and oxide forms, each of them with their own processing path, flotation for the former and SX-EW for the latter (see Figure 2.13).

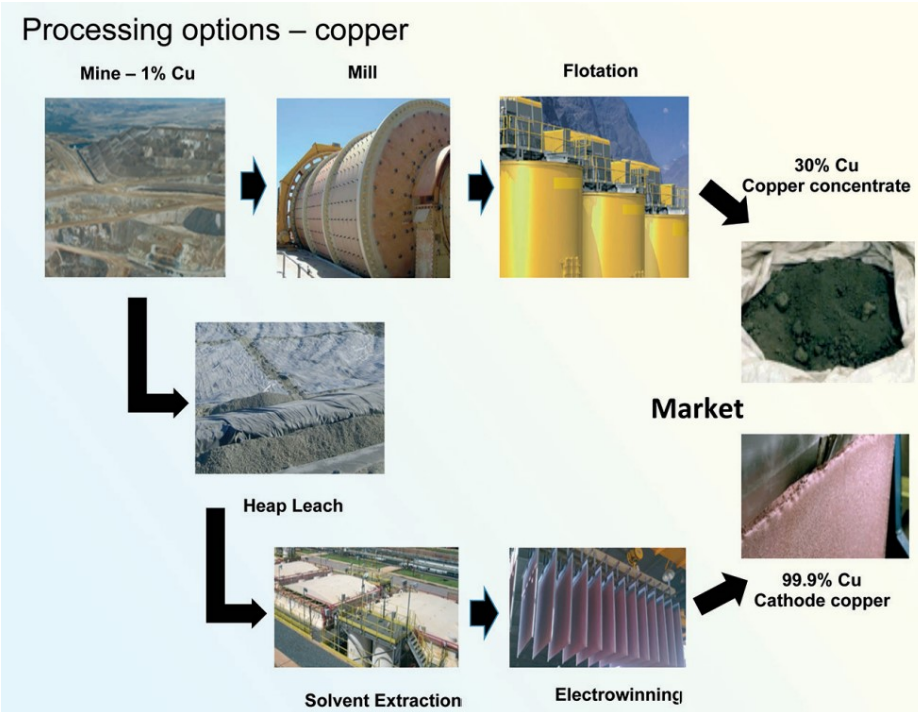


Figure 2.13: Copper processing options. From Arndt et al. (2017).

The run of mine (ROM) is usually concentrated via flotation to obtain copper concentrates. In order to do this, the ore is crushed and milled to sizes between 10 and 200 microns to optimize the liberation and then mixed with chemicals in a flotation cell in which air will be fed from the bottom creating a copper rich foam on the top to be recovered (roughly 30% copper). The foam is then dried and sold as copper concentrates. During this process, as ores usually contained traces of gold, silver or molybdenum among others, these metals are obtained as secondary concentrates, yet molybdenum requires a special concentration process to be recovered.


Figure 2.14: Major international trade flows of copper ore and concentrates. From ICSG (2021).

In the case of oxidized ores, they follow a different processing track. They are often mined near surface and then placed as large piles or pads built on impermeable liners to then be lixiviated with acid or less common, with bacteria via bioleaching. On the top of the pads the diluted sulfuric acid is dripped, while from the bottom, air is fed to ensure a greater recovery of copper. The pregnant solution is then recovered from the base. In the case of bioleaching, this method is used for chalcocite-rich supergene ores. Copper dissolution and oxidation takes place due to bacterial activity. Nonetheless, its performance is highly sensitive to temperature, air, and acid flux control. The copper from the pregnant solution is then recovered through solvent extraction followed by electrowinning (SX-EW), providing concentrations higher than 99% copper cathode (Arndt et al. (2017)). Cathodes are categorized in two marketable groups: the smelter and refinery levels. In this case, commercial cathodes are high-grade products and can be sold as refined cathode, whereas low-grade cathodes require to be refined (ICSG, 2014).

### 2.3.2 Smelter Production

Smelting comprises all pyrometalurgical processes employed to produce copper metal. Moreover, depending on the sources of materials used the smelter production falls into two groups to produce blister, anode, and other smelter-level products. Products made from concentrates, precipitates, and low-grade electroformed stock from SXEW and RLE plants are part of the first category also called primary smelters; the second, or secondary smelters, produce products made from copper scrap and low-grade electrowinning cathodes (ICSG, 2014).

The output is highly concentrated in China, which produces copper mainly for domestic consumption. During 2020 (see fig. 2.15), China generated c.a. 50% of world copper smelter production. In second place was Japan (8%), followed by Chile (6%), and Russian Federation (5%). On the other hand, in terms of trading, Chile holds the first place leading anodes exports, mainly to China, the European Union, and the United States (see fig.2.16).

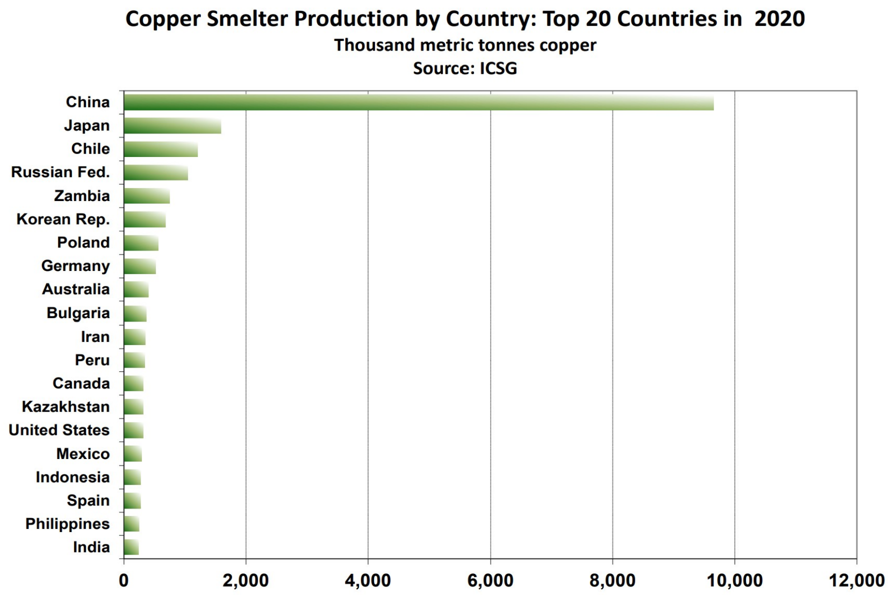


Figure 2.15: Copper Smelter Production by Country: Top 20 Countries in 2020. From ICSG (2021)


Figure 2.16: Major international trade flows of copper blister and anodes. From ICSG (2021)

### 2.3.3 Refinery Production

ICSG (2014) divides copper refinery production in three statistical categories: primary, or copper refined through fire or electrolytic cells; secondary refined undergoes the same processes as primary refined, but its source of refined material comes from scrap that was converted to anode or fire-refined by the smelter; electrowon, which comprises high-grade SX-EW refined production. Figure 2.17 provides the distribution of refined copper into the three different categories previously defined.

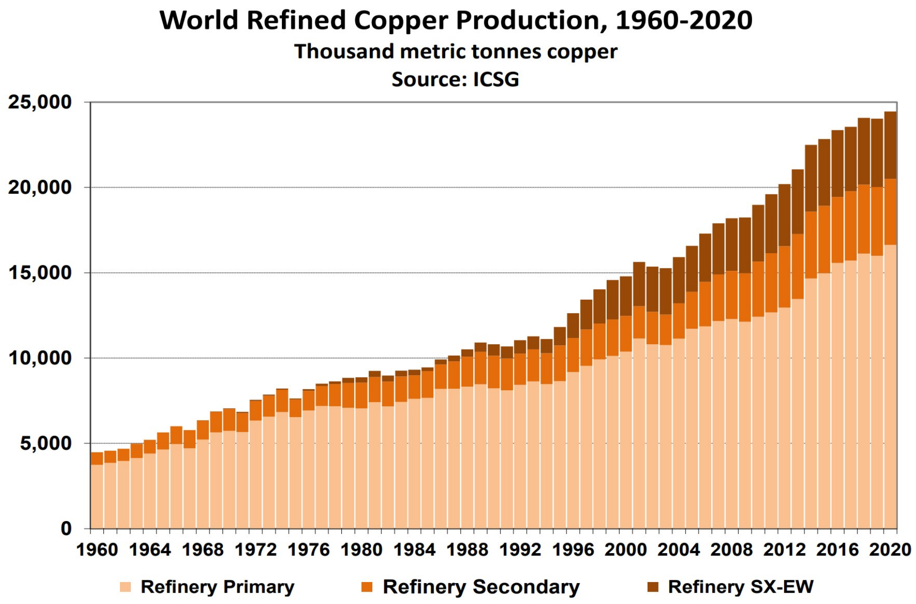


Figure 2.17: Major international trade flows of refined copper. From ICSG (2021).

In this case, the industry is highly led by primary refined copper, yet with an increasing share of secondary refined copper and SX-EW. On the other hand, in 2020 China produced 41% of world copper refined production, followed by Chile (10%), Japan (6%), and Congo (5%).

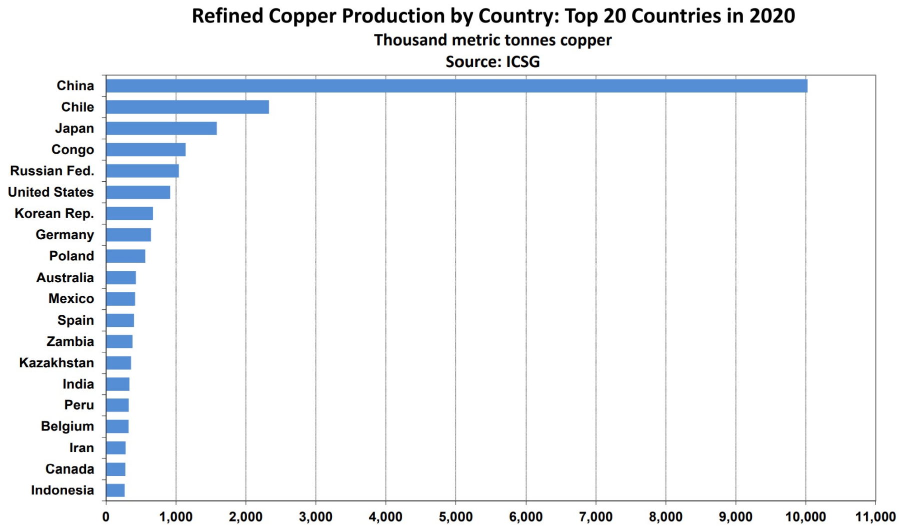


Figure 2.18: Refined Copper Production by Country: Top 20 Countries in 2020. From ICSG (2021)

Finally, when it comes to trading refined copper, Chile holds the first place, exporting mainly to China, the European Union, and the United States. In a minor scale, DRC and Poland trade mainly to European Union.


Figure 2.19: Major international trade flows of refined copper. From ICSG (2021).

## 2.4 Market analysis

### 2.4.1 Supply

The supply of copper concentrates is highly concentrated by a few big producing countries, where Chile holds roughly a 26% of the world supply, followed by Peru (11%), and China (9%).

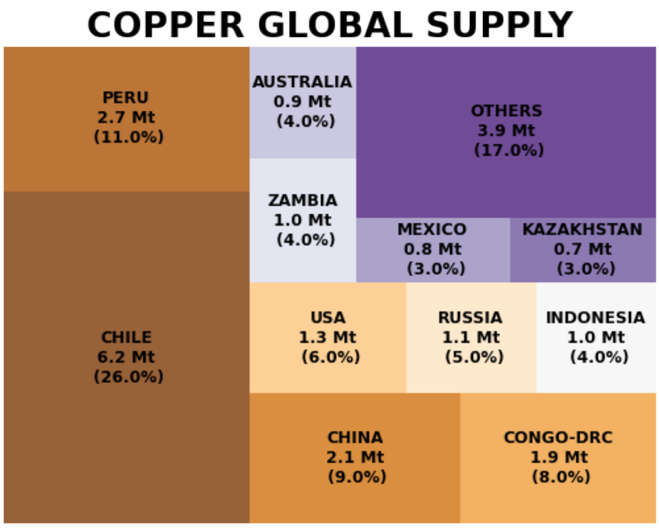


Figure 2.20: Global copper supply per country share (year 2021). Own elaboration adjusted from CRU database.

Furthermore, over the last five years, the total output of this metal has been quite constant averaging 20.2 million metric tons per year, with an average yearly growth of +1% (World Mining Data, 2021). Moreover, COVID-19 disrupted production as some mines put their operations on hold which contracted the total output compared to 2019 with roughly -3%. Nonetheless, this impact was less significant as expected by analysts Fitch-Solutions (2021):

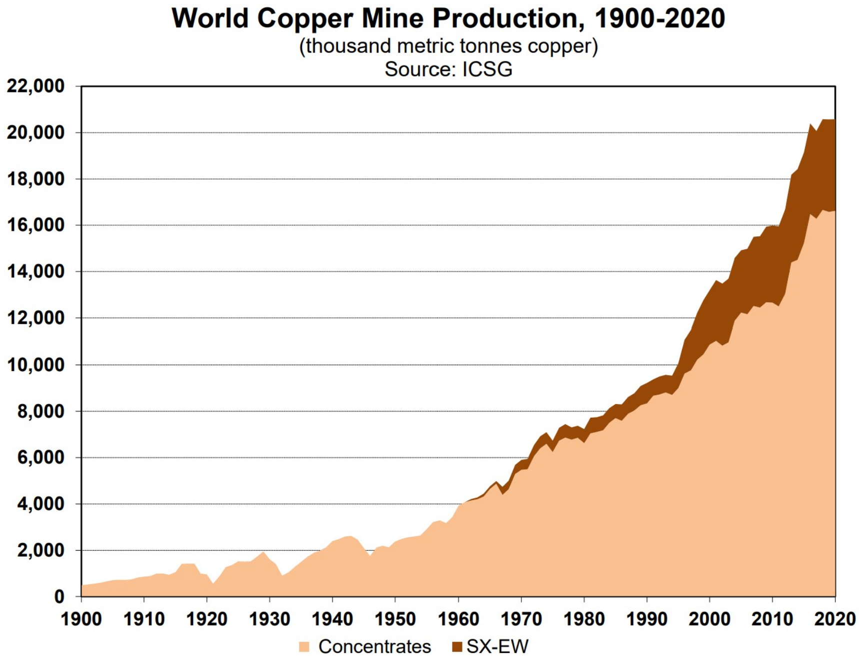


Figure 2.21: Global copper supply evolution. From ICSG (2021).

On the other side, according to Metso:Outotec (2020) an output growth is expected mainly as a result of the low effect of Covid measures in production, mines resuming operations, and due to numerous new projects upcoming such as Grasberg, Cobre Panama, Quellaveco, Oyu Tolgoi, QB2, Spence. Therefore, the market is expected to grow 2.1% per year that would drive total supply output to 23 mtons in 2024. Nevertheless, Fitch-Solutions (2021) warns of key downside risks associated with the decline of average grades, specifically in Chile. This is the outcome of high grade ores being commonly mined at the beginning to improve discounted cash flows of the project, which could shutdown low-grade mines in the long term.

Conversely, experts also warn about the current political framework in Chile and the uncertainty of the outcome of the new constitution. Given that this will impact mining industry and legislation, as impacts of COVID-19 are intended to be financed by rising the taxes in mining. This is delaying investments in mining projects as its Investment Attractiveness Index has fallen over 10 points which is making Chile struggle in production expansion (Financial Times, 2021).

ICSG (2021) detected financial and operational risks in copper supply to meet the upcoming increase of demand. The main findings are listed below:

- **Overall increase in costs:** mining costs due to decline in ore grades, Energy costs, as fossil fueled mines will face climate change policies e.g.: carbox taxes. Utilities, such as water supply given drying mining districts, which force some of them to desalinize water through inverse osmosis increasing costs. Increase in royalties/taxes as it has become a priority for some governments to develop their economies' incomes from their natural resources. Metso:Outotec (2020) notes that other side-effects of shortage of supply are the constant decreasing costs associated to treatment and refining charges (TC/RC) in the last years mainly due to a high oversized smelting capacity being present.

- **Disruption of operations:** more frequent labour strikes as they are prone to increase when refined prices are high and GDP is growing faster. Operations in high political risk countries can jeopardize logistics which are crucial to ensure supply.

### 2.4.2 Demand

Consumers of copper are likewise concentrated in a few countries i.e.: China, Japan, Europe, Korea, and India mainly (see Figure 2.22). On the other hand, data provided by WITS (2021b) reveals that a great part of their consumption is based on imports which is a big driver in the price of this commodity . In the case of China, 70% of their consumption is imported, holding the 61% of global imports, Japan (13%) and the European Union (10%).

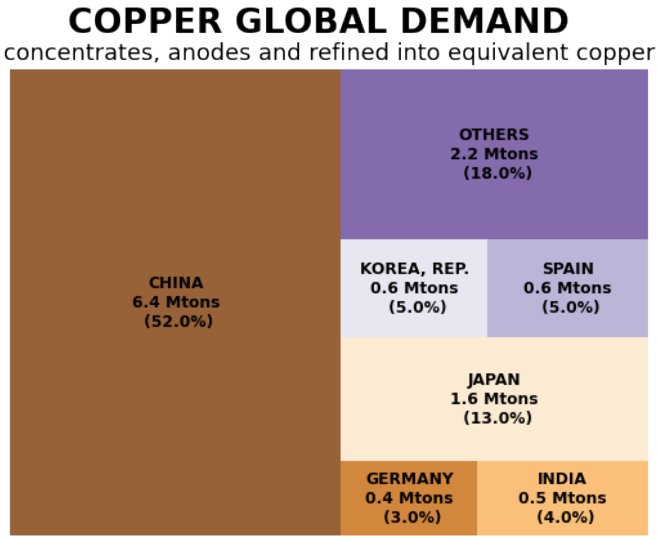


Figure 2.22: Global copper demand (year 2021) in equivalent copper i.e.: concentrates (30%), anodes (95%), refined copper (99.99%). Own elaboration adjusted from WITS (2021a), WITS (2021c) and WITS (2021d)

Additionally, the copper price has been quite volatile in the recent years (see Figure 2.23). It can be noted that from 2003 onwards the price of copper rose from about 84.3 cts/lb to around 400 cts/lb in 2008, when China overtook the United States as the largest copper consumer. In the same year, following the 2008 financial crisis, the price fell sharply to around 150 cts/lb and then reached a record high of 450 cts/lb in early 2011, partly explained by the growth of demand in emerging economies at pre-financial crisis levels. Since then, the price of copper has continued to be very volatile, fluctuating between 215 and 350 cts/lb until mid-2020.

On the other hand, as reported by Smith (2021), copper's price went through a cycle of high volatility but with a strong upward tilt in 2021, closing the year with an average of 422.6 cts/lb, the highest annual price ever recorded; the recovery of the Chinese economy particularly in the manufacturing, exporting and domestic consumption sector, which in turn is reflected in a continuous increase of copper imports (Cochilco., 2022). However, the key factor of the increase of demand and price has mainly been supported due to expectations of short-term refined metal shortages and low inventories on metal exchanges. This framework despites the endurance of the Covid-19 epidemic, growing inflation expectations in the United States, the strengthening of the currency, and the

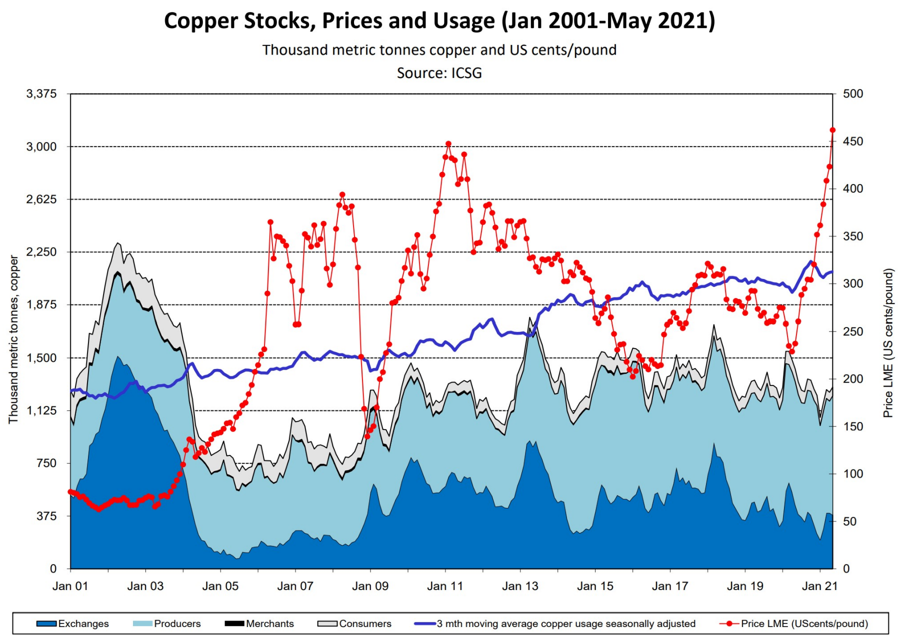


Figure 2.23: Copper stocks, prices and usage evolution (Jan 2001-May 2021). From ICSG (2021)

likelihood of a Chinese housing market collapse. According to (Cochilco., 2022), copper prices have been rising owing to three main factors: low stockpiles of refined copper on metal exchanges, the vulnerability of copper output, and the revival of GDP in the major metal-consuming nations.

Nonetheless, (Cochilco., 2022) forecasts a decreasing cycle of the average annual metal price to commence in 2022-2023. This is mainly attributed to the slowdown in economic growth rates of the main copper consumers – China, the Eurozone, the United States, and Japan that concentrate more than 80% of the metal's demand. However, the low level of inventories on metal exchanges will persist over much of the projection horizon, limiting downward pressure on copper prices.

Alternatively, copper inventories have been declining and have reached levels last seen 15 years ago, allowing them to only cover 3.3 weeks of demand. Smith (2021) predicts prices might rise to 650 cts/lb in the medium term if the market shortfall continues. This is where scraps play a big role as in the upcoming years, they could contribute in the deficit of supply, yet if their usage by smelters and refiners does not increase as predicted, this would mean a depletion of the stock of this metal in 2024 dragging with it an increase of price.

Figure 2.24 reflects the theory that the balances produced from such supply–demand analyses should indicate whether markets are expected to be in surplus or deficit in the next years, and hence whether prices are likely to decrease or rise over that time. Furthermore, supply–demand research, when combined with information on current stock levels, provides an estimate of the size of expected future market imbalances and, as a result, the potential magnitude of price fluctuations. The high density areas (dark hexagons), shown in

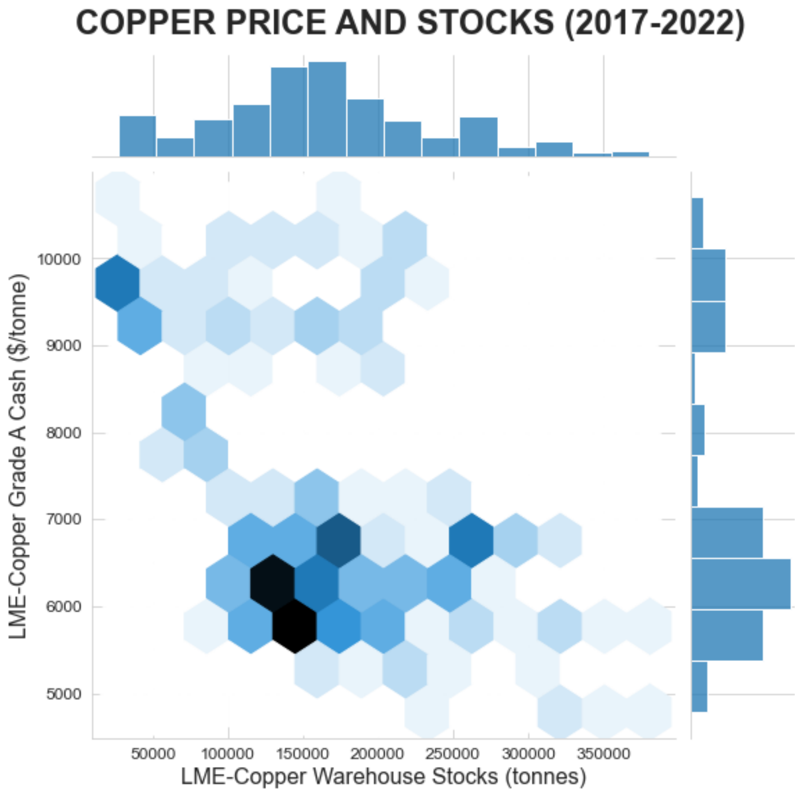


Figure 2.24: Global copper supply versus price. Own elaboration adjusted from S&P Global database.

figure 2.24, give an insight about the inverse proportional trend between the price and the available stocks. However, (Darling, 2011) remarks this approach is not accurate enough to forecast price behaviour.

In addition to the growing momentum of speculative factors, as copper has been called "the new oil", Smith (2021) notes that price could also be boosted in the longer-term by emerging industries such as EV and semiconductors bringing prices close to 1000 cts/lb.

### 2.4.3 Political risks

#### Introduction

Trade barriers aside, most administrative and political disruptions on supply are in mineral-rich rather than importing countries. Even where many known mineral deposits are awaiting development, and seemingly able to produce profitably with existing technology, their exploitation depends on a benign, or at least neutral, social, political, and economic environment.

In many mineral-rich countries, the environment is anything but benign. Moreover, mineral enterprises commit considerable resources to developing mines over many years before commercial production starts. The prospective lives of their investments stretch many more years from start-up. At each stage, the technical and economic risks are high, with an ever-present possibility that the investment will fail. Furthermore, after the investor has committed resources to developing a deposit, they are locked to the project. The company's capital is sunk, and it is impossible to transfer the investment to a more accommodating environment. Thus a mining company's bargaining power with the host country weakens considerably after its capital is invested (Darling, 2011).

Accordingly, shifts in copper-rich countries' governments, increasing royalties, new climate-change regulations, and recent short-term supply interruptions, notably owing to the Russia-Ukraine conflict, have all been identified as political risks and will be reviewed in this section.

Figure 2.25 provides an overview of the overall sentiment in regards to political risks concerns in the short-term:

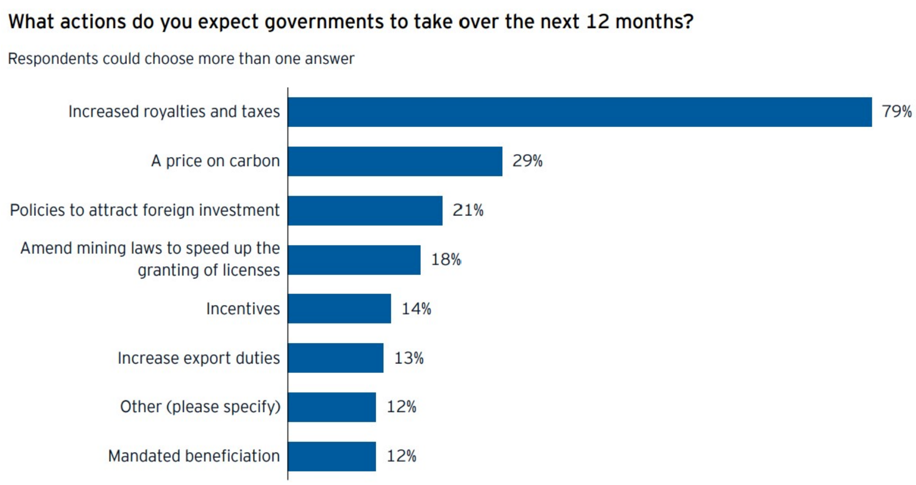


Figure 2.25: Political risks in the short-term. From Ernst and Young (2021).

**Global**

- **Trade policy changes**

  During 2021, the G20 has proposed a global minimum tax of 15% to the countries they sell goods to. On the other hand, the EU proposed to fix a carbon tax on commodities imported from 2026 to protect European industries from competitors which are not subjected to the same measures (Ernst and Young, 2021)

- **Ukraine war**

  Fitch-Ratings (2022) remarks that due to the fact that Russia produces 4% of both mined and processed copper, the Ukraine war and subsequent sanctions may have an impact on supplies in the short term. Likewise, the same institution as raised its global metals and mining price assumptions due to the conflict, copper in particular has been raised an average of 9% in the following 2 years, whereas it estimated a 4% increase of price in the long-run.

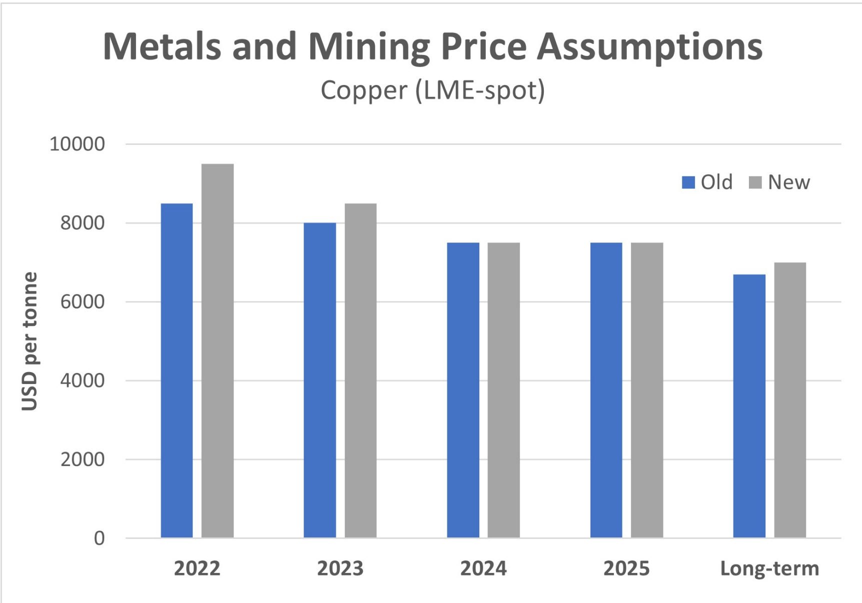


Figure 2.26: Metals Mining price assumptions updated on Ukranian conflict as of March 2022. Own elaboration adjusted from Fitch-Ratings (2022)

**Key countries**

- **Chile**

  Currently, Chile is revising its constitution to replace the current free-market-oriented one created during General Augusto Pinochet's military dictatorship. The new constitution is in progress, but numerous changes have already caused concern in some industries. Chile's constituent assembly adopted an early stage plan that might lead to the nationalization of the country's copper sector, infuriating mining companies in the world's top copper producer. In particular, Minera Escondida would be the first mining company with foreign capital to pass into Chilean hands if a process of nationalization of copper should take place.

  Some late concerns address possible impact supply interruptions owing to water scarcity in Chile. Additionally, following huge protests against socioeconomic inequities, Chile is now developing a new constitution, with politicians pressing for changes to a water system that has depended mainly on private sector and market forces to assign rights and deliver services. In fact, according to Attwood and Biesheuvel (2021), during Aug-21 some mines of BHP Group and Antofagasta PLC were forced to stop pumping groundwater for three months. In that context, an environmental court took the unusual step of temporarily halting Cerro Colorado's use of water from the Lagunillas aquifer since Oct-21 while it hears a case accusing the business of causing environmental harm.

  Along with the previously water-related issues and long-standing challenges like diminishing grades and a lack of new projects, Aquino and Cambero (2021) note there is rising concern in Chile by a long shot over onerous taxation and the prospect of state appropriation.

  Furthermore, the mining industry will be reformed because Chilean society has agreed that major international copper firms are not paying their fair share. There is widespread consensus that, for example, the present royalty of 40% on earnings is insufficient, and that additional copper processing within the nation is required. The measure to increase mining royalty might jeopardize up to one million tonnes of production (Aquino and Cambero, 2022).

- **Peru**

  The recently elected president of Peru, Pedro Castillo, has promised to overturn Peru's decades-old constitution, confiscate up to 70% of revenues from mining corporations doing business in the nation, and impose new levies on mineral sales. However, his campaign has softened its stance on nationalization, but it still believes that extractive industries are underpaying taxes. Under the Castillo administration, tax stability agreements would be reviewed, as well as royalties paid by mining and hydrocarbon corporations, which would presumably be increased. Moreover, Peru wants to enhance local and indigenous communities where mining takes place by improving infrastructure and environmental regulations.

- **Democratic Republic of Congo and Zambia**

  Both countries have carried a bad reputation from investors due to changing regulatory regimes, difficult working conditions, and corruption taking place. However, according to Denina and Reid (2021), big miners are reconsidering investing in Congo and Zambia as the price of copper surges. In the same way, recent democratically-elected president in Zambia, Hakainde Hichilema, has improved the overall political risk outlook for the country as he promises more business-friendly policies in regards to mining compared to his oppositor (Fitch-Solutions, 2022). Similarly, Denina and Reid (2021) mentions that investors claim that the smooth start-up of large projects in Congo, such as Ivanhoe's Kamoa-Kakula mine, lends comfort to corporations considering an investment there.

- **China**

  As previously stated, China is a relevant copper producer (9% according to Figure 2.20), but it is even more of a major copper consumer (52% according to Figure 2.22). As a result, China wields considerable power in the copper market. Moreover, China has seen the fastest growth in EV demand among the world's major economies, with EV sales increasing by nearly 190% last year (Norland, 2022). Mining.com (2021) mentions that since 2010 Chinese investments account for a total of $16 billion and have aimed to purchase copper mines overseas in order to fill this demand gap and secure the price of copper. However, this barely meets 20% of the domestic demand as seen in Figure A.1 in the Appendix.

  Additionally, Chinese companies give the government infrastructure in exchange for access to minerals. This procedure is frequently not transparent and susceptible of corruption or other unethical practices which have posed a risk to supply. Narang (2022b) gives some recent examples of this, when copper supply was disrupted in Minmetal Resources' Las Bambas mine (2% of global supply) in 2016 after communities in Peru had intermittently blocked an important route for 400 days. This occurred as a result of the Chinese company violating environmental agreements, namely copper trucks that damaged the villagers' crops and animals and failed to give them any financial compensation. In a similar fashion, Narang (2022a) alleges that workers at the Tenke Fungurume mine in the DRC were having problems with work safety and also claims that employees had been bribed to conceal accidents since the mine was owned by Chinese companies. Later, Felix Tshisekedi - the president of the Congo - established an investigative commission to look into claims that Chinese corporations may have defrauded the Congolese government of royalties from the mine.

# Chapter 3

# Mining Finance

### Introduction

The time it takes for a mine to generate any revenue may be lengthy, particularly when the time between early exploration and commercial production is factored in. A significant mineral deposit's lead time from discovery to investment decision is often more than a decade (Darling, 2011). Prior to capital investment a feasibility study is conducted, which requires a thorough analysis of various aspects into the proposed resource project. Predominantly focusing on multidisciplinary engineering designs to highlight the main challenges related to mine development and planning. Thus, these technical concerns must be addressed in every assessment of potential resource projects. Additionally, it is almost impossible for the existence of two equal orebodies, therefore no two development projects will be the same. This results in the added complexity of each project requiring their own unique development and engineering designs. However, the primary goal of FS is to establish whether or not a development opportunity is financially viable, not merely technically feasible. Technical difficulties are sometimes perceived as the major focus of FS, while in truth, they are the foundation upon which an asset delivery and business strategy are formed.

Mackenzie and Cusworth (2007) refers to the feasibility study process as the one responsible to demonstrate that not only technical challenges have been sufficiently resolved, also the broader commercial, economic, and social issues have been included in the development of a comprehensive business plan. Alternatively, NI43-101 (2011) defines a feasibility study as "a comprehensive study of a deposit in which all geological, engineering, operating, economic and other relevant factors are considered in sufficient detail that it could reasonably serve as the basis for a final decision by a financial institution to finance the development of the deposit for mineral production". The feasibility study method deals with uncertainty, and as a result, a phased and iterative research strategy has emerged. This study process is often divided into three stages: the conceptual or scoping phase, the preliminary or prefeasibility phase, and the final or definitive phase. From a financial perspective, each of them provides sequentially increasing clearer insight about the capital estimated costs (capital and operational).

## 3.1 Capital investment

Due to the nature of mining, this industry is considered as one of the most capital-intensive sectors(Darling, 2011). The capital investment needs of the sector vary depending on the location, mining method, and type of each mineral deposit. Besides the mining and the related processing facilities required to generate a marketable commodity, an associated infrastructure is generally required. For example, the need for capital investment is reduced if the mine is located near an established town or mining region, as water supply, power and established transportation infrastructure is pre-existing. However, current facilities will almost certainly need to be upgraded or modified to increase efficiency.

Similarly, to a feasibility study, a "Bankable Feasibility Study" (BFS) is described by Mackenzie and Cusworth (2007) as a document that explains the technical risks involved in a mining operation, which outlines solutions for mitigating risks and assessing possible economic returns at various commodity prices for a specific capital investment. Benning (2000) defines BFS as "a detailed presentation of the technical, financial and legal aspects of a viable mining project, on which the Bank will perform its due diligence exercise". There is no existing standard bankable document, as each bank determines what is necessary in a document based on their own criteria, to justify funding a mining project. Likewise, there are four broad categories of risk involved in the examination of a mining project. They are used by financial institutions contemplating funding a mining project or a mining firm seeking funds to finance their project: (1) bank risk, (2) country risk, (3) company risk, and (4) project risk.

However, if companies want to optimize corporate leverage a better indicator is to look at Debt/EBITDA than at Liabilities vs Equity on balance sheet. This is due to the fact that balance sheet values are not related to actual underlying value or cash flow generation. Leverage at an asset level however is best described by original Debt vs Equity injections.

Darling (2011) notes there has been a near-universal trend for mines to grow in size over time. Unlike many other productive industries, the mining sector not only has a high capital expenditure need before production can commence, but it also has significant ongoing requirements throughout the mine's existence. In addition to regular capital expenditures for the replacement of equipment and maintenance, the mining sector must cover the cost of extracting ore from deeper and farther-reaching areas of the deposit, as well as maintaining output in the face of diminishing ore grades. As mining advances and companies gain a better grasp of the properties of their ore deposits, they will frequently identify potential new ore that may support further mine expansion (Darling, 2011).

Accordingly, once the capital costs have been properly estimated, mining projects must define the capital structure, namely the share of debt and equity. Wellmer et al. (2008) mentions it is feasible to fund mining projects entirely using debt in industrialized mining countries, such as Canada and the United States. Banks in underdeveloped nations will compel mining owners to put up equity. The conditions might vary, but a typical ratio is 3:1, which means 25% ownership and 75% loan capital. When a project is entirely financed with debt, the computation of an internal return on equity is null and void. The net present value (NPV) is used as an economic criteria in this scenario. Figure 3.1 displays the capital structure decision of some copper producing companies.

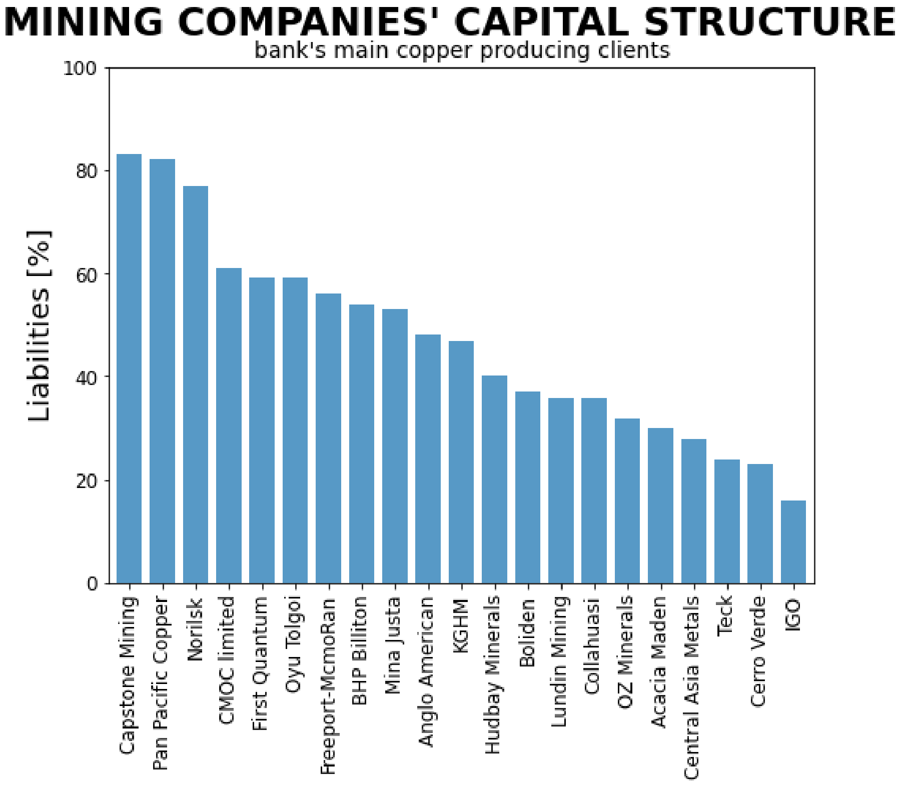


Figure 3.1: Share of liabilities from total assets for individual mining companies. Own elaboration based on the financial statements of individual mining companies.

However, the capacity of the project to repay the loan with a high degree of certainty, based only on proven and probable reserves, is a significant consideration for the equity to debt financing ratio. Wellmer et al. (2008) notes that a cash flow to debt coverage ratio of at least 1.2 to 1.5 is necessary for debt financing in general, measured as the ratio of cash flow to the amount of debt plus interest. Moreover, if the criteria that total proven and probable reserves have a lifetime of at least twice the time necessary to repay the loan is not met, the bank will almost certainly lower the percentage of debt financing in proportion to the reserve deficiency.

Lastly, in terms of interest, many project-financing loans do not have a fixed rate and have been instead based on the LIBOR rate (London Interbank Offered Rate). The premium over the LIBOR rate accounts for both the risk of a mining project and the risk of the country. However, recently LIBOR has been phased out completely, and instead being replaced by risk free rates - concept remains the same, a floating benchmark plus risk premium. In order to do an economic analysis during the exploratory stage, we must make a fair estimate about future interest rates (Wellmer et al., 2008).

## 3.2 Financing

The capacity of a mining project to raise funds is frequently determined by its phase of development. Initial stages normally need to be funded with equity; and the more it progresses through the development cycle, the more likely it will need to secure loans. The common means of funding mining projects at various stages of development, from early exploration through project completion when lenders believe it to be technically complete, are described in Figure 3.2 below.

| Development phase | Type of funding | Source of funding |
|---|---|---|
| Prospecting<br>Initial Exploration<br>Advanced Exploration | Equity<br>Equity<br>Equity/Venture Capital | Shareholders<br>Shareholders<br>Shareholders and Specialized Resource Funds |
| Pre-Feasibility Study | Equity/Venture Capital<br>Capital/Quasi-Equity | Shareholders and Specialized Resource Funds<br>Resource Funds and Selected banks |
| Bankable Feasibility Study | Equity/Quasi-Equity/Debt (with recourse) | Shareholders, Selected Banks and Commercial Banks |
| Construction | Equity/Debt (limited recourse) | Shareholders and Selected banks |
| Post-Commissioning (completion) | Equity/Debt (non-recourse) | Shareholders and Selected banks |

Figure 3.2: Typical types of funding for various mining project phases. Own elaboration adjusted from (Benning, 2000).

### 3.2.1 Equity financing

Despite of how developed a project might be, equity is the most frequent capital base; even the most economically robust enterprises will never be entirely funded with debt. In this regard, Benning (2000) comments most mining projects will have a debt-to-equity ratio ranging from 30:70 to 60:40 (see Figure 3.1).

At an early stage, equity is raised commonly by offering equity shares to the public by listing the company on the stock exchange, which is known as Initial Public Offering (IPO). Given the potential gains during the transition from private to public shares, institutions like venture capitalist usually acquire positions in an early stage whereas very few lenders are willing to consider providing funding. The term "venture capital" refers to equity that is supplied as a speculative investment. It is usually not meant to be long-term capital, but rather cash invested into a firm for a specific period of time during which the investor expects a significant increase in the share price before exiting the transaction. After IPO takes place, the company can issue a secondary equity offering or SEO, by offering equity shares to the public when already listed in the market. Finally, many mining companies also carry out private placements afterwards, which consists in offering shares to high net worth investors in private.

Alternatively, quasi-equity debt is also a widely used instrument to raise capital. This is in fact debt arranged in such a manner that it is reflected as equity. To be more precise, it typically takes the shape of convertible debt that may be exchanged to conventional stock if the share price rises. In consequence, quasi-equity is generally subordinated to senior debt as an exchange for the option of converting it to equity. This reduces leverage and improves debt capacity as it is reported as equity in the balance sheets (Benning, 2000).

In the same way, private investors, stock market listings, and rights issues are common sources of equity, but it can also be founded internally. However, mining is typically cyclical, resulting in unpredictable stock prices and investment patterns. Mareels et al. (2020) notes two main challenges for mining companies when it comes to raise equity:

1. **Volatile valuations:** mining projects are highly sensitive to spot prices when compared with similar industries e.g. Mining correlation is 93%, whereas oil and gas is 84% and 60% pulp and paper. Moreover, intrinsic business value obtained through discounted cash flows has proven a 1.4 higher gap with the book value, which reflects investors confidence. This low confidence, compared to real performance decreases financial attractiveness of this industry to public equity.

2. **Cyclical capital expansion:** the capacity to raise funds is linked to price levels, which reflects on mining businesses tending to go through unusually "peaky" capital-expansion cycles, due to a combination of the strong correlation between prices and valuations. This brings as a result the fact that many investors miss to capitalize when prices go up because of under-investing during downcycles.

### 3.2.2 Debt financing

The capital expenditures necessary to construct new mines are so substantial that even the major players are looking to boost project finance rather than relying on cash flows from current operations. External debt maximization has a two-fold benefit: first, it frees up financial resources for alternative investments, and second, it improves shareholder returns due to the effect of leveraging.

Furthermore, the possibility of financing for mining projects is determined largely by the project's financial viability, the sponsor's criteria, and the overall risk profile of the project or corporate entity. Benning (2000) addresses this explaining that financing is categorized as Corporate Loan, Project Finance, or Venture Capital, and describes their risk-reward relationship in Figure 3.3 below.

Figure 3.3 again shows how debt capacity is acquired from a certain level of risk appetite from which lenders feel comfortable. This is frequently due to the fact that the risks are too large for banks to earn simply a 'debt return,' and that such risks must be carried by shareholders who stand to benefit from any possible upside.

Banks usually prefer larger mining companies with greater diversified products and locations where they operate. This is mainly because diversification of commodities also benefits in moderating revenues and exposure to single commodities that are generally volatile due the cyclical nature of their markets. In

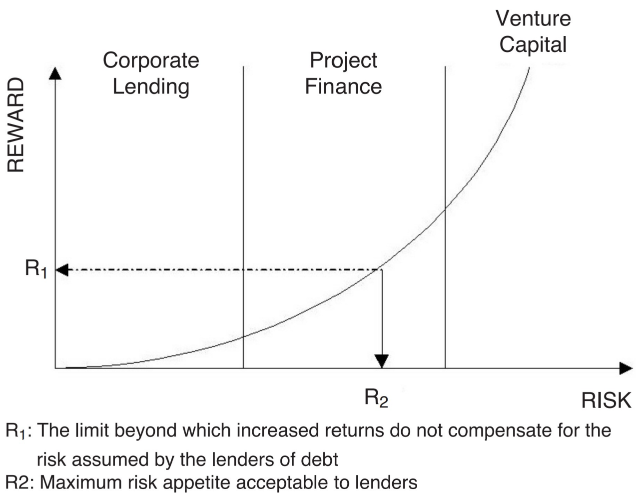


Figure 3.3: Categories of finance in the Risk-Reward relationship. From (Benning, 2000).

addition, credit approval for funding is generally easier to acquire for companies with good balance sheets. This is because a typical corporate loan comes with complete liability against the balance sheet of the project sponsor. In other words, because the project is not 'ring-fenced' from the rest of the firm, the lenders will be able to reclaim payments from the entire company if the initiative is not financially successful.

Generally, commercial banks would not consider lending money to a mining project until a BFS has been completed and audited by independent technical specialists. Banks often offer funding in the form of corporate loans (full recourse) or project finance at this point (limited or non-recourse). The selection of finance sources is especially crucial in the mining sector, whose expansion is defined by protracted investment cycles and generally long payback periods as a consequence of the large capital intensity of mining projects.

### Corporate debt

Corporate debt instruments include bank corporate loans and bond issuance. In this case, debt is placed against corporate assets of the company. Better explained, a typical corporate loan comes with complete recourse against the balance sheet of the project sponsor. According to Benning (2000), these loans are also normally only available for cashflow generating senior mining companies. Some common types of corporate loans are:

- **Overdrafts:** this corporate loan functions in a very comparable way to a personal overdraft. Corporations can obtain short-term and conveniently accessible cash by establishing an overdraft with the bank without informing the bank in advance. Since it is typically used to fund temporary deficits in a company's capital, an overdraft is also known as a working capital facility.

- **Term loans:** a term loan, unlike an overdraft, is a more formal lending transaction in which a lender agrees to lend you a certain sum for a fixed duration. The debt is typically paid in installments or in one lump sum at the completion of the period, based on the mandate stipulated upon with the lender. Term loans are usually spanning one to five years. Additionally, cash can be received in a single payment or in a series of smaller installments known as 'tranches.' Unlike an overdraft or an open-end credit facility, once a loan is repaid, the money cannot be borrowed again.

- **Revolving credit facilities:** a revolving credit facility is comparable to a term loan in that it allows companies to draw up to a certain amount for a specific duration of time. Unlike a term loan, nevertheless, money can be drawn down and repaid in installments. Credits are accessible to businesses throughout the loan, similar to an overdraft, except at the completion, when the outstanding amount must be paid according to a defined timeframe.

- **Bridging loans:** finally, a bridging loan is a short-term loan that is intended to be utilized in certain situations. It is usually part of a revolving credit arrangement, in which the bank guarantees cash in the event that the firm is unable to secure funds via other means or if that funding is deferred for whatever reason.

On the other hand, companies choose to raise cash through a bond issuance when banks are hesitant to lend money owing to the risk of default. This alternative, is however adaptable since it can be tailored to the company's investment needs and utilized for any purpose. One of the key causes is that investors do not monitor compliance with regulations relating to the efficacy of underlying investment projects on a regular basis.

Furthermore, Sierpińska-Sawicz and Bak (2015) explains this option allows the issuer to divide the issuance into tranches to guarantee that the financing needs of the investment process are met, set a redemption date for the tranches, and choose the type of asset it can pledge. Furthermore, this instrument offers diversification of funding sources, longer duration, and often looser restrictions than bank loans.

Nevertheless, bonds are actually less flexible as all bank debt may be prepaid - without penalty - at any point in time. Moreover, bonds often have a non-callable period, followed by a period with a prepayment penalty, before they may be repaid at par before the original due date. Lastly, if a company wants to do something outside the terms, bonds are inflexible, while banks might just agree with changes as long as the underlying risk remains acceptable. This is largely a function of responsiveness, as the issuer can speak to the banker, but not to the bondholder.

Bondholders' terms, on the other hand, are described by Benning (2000) as sometimes overly onerous, prohibiting enterprises from pursuing this type of financing. Companies are cutting back on investment initiatives and having difficulty finishing ongoing investments. This not only extends the time it takes to implement the investments, but it also decreases their rates of return. Furthermore, businesses lose financial liquidity, and if they fail to pay bills on time, they must incur penalty interest, which raises financial expenses.

Furthermore, the use of other kinds of financing, such as a bank loan or the issuing of stock, is not precluded by bond offerings. During a period of economic expansion, the stock market begins to satisfy expectations, and businesses are increasingly eager to seek financing through the issuance of shares. According to market timing theory, if entrepreneurs feel their stock will be undervalued until the market recovers, they will postpone their choice to obtain financing through the stock market. During periods of economic depression or low economic activity in the industry, however, the reverse pattern happens. Companies are eager to raise capital through a bond offering under such conditions.

### Project finance

For projects there is a non-recourse debt finance option, which is essentially that assets are pledged as collateral. This is available for both junior and senior mining companies with assets at development stage. This type of financing is more complex and expensive than corporate finance.

Figure 3.4 displays a typical project finance structure for mining projects. The principal players are the sponsor which are developing the mining project and the lender, or a consortium of lenders, the players that will provide the debt financing. To raise the debt financing the sponsor will have to set up a special purpose vehicle or SPV which will be ring fenced. Ring fencing is achieved when SPV has its own board of directors, its own bank accounts, its own financial reports, and accounting.

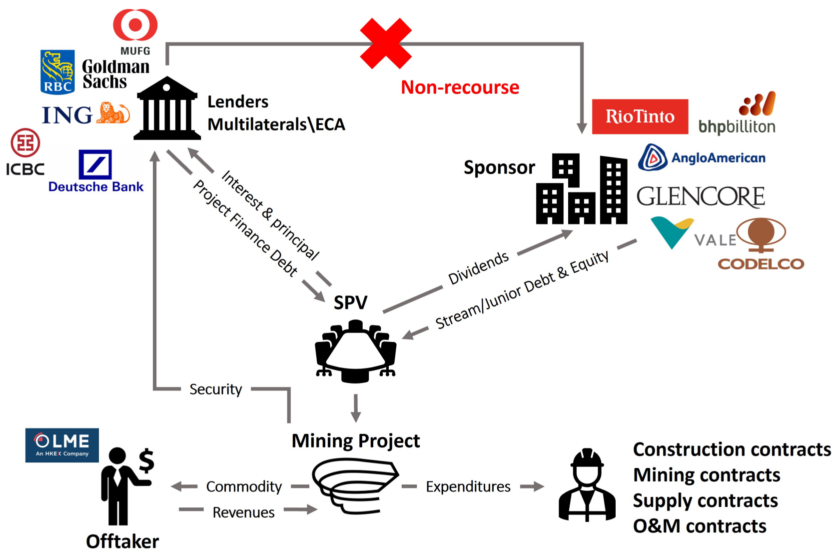


Figure 3.4: Project finance structure in mining projects. Own elaboration.

By means of project finance debt, the SPV will raise the debt financing from the lender, and equity financing from the sponsor to develop the project. In this case, the lender will take the assets of the SPV as security and these assets may include the equipment, processing plant, and mining licenses. Once the mining project is operational and generating cash flow, it will repay the interest and principal to the lender, and the remaining cash flow will go to the sponsor in the form of dividends. However, if the project does not perform and the cash flow is not sufficient to pay the interest and principal, the lender cannot go after the assets of the sponsor, so the loan that the lender provided to the SPV will be on a non-recourse basis. This is because the lender will not have recourse to the sponsor, therefore the lender can only rely on the cash flows that will be generated by the SPV, and will have recourse only to the assets of the SPV. On the other hand, if the SPV is not ring fenced, in some jurisdictions the lender may have full recourse to the sponsor, both during the construction and operations phases. In consequence, ring fencing provides limited liability for the project sponsor if there is a problem with the project, namely financial or environmental related.

However, it is important to remark that only multi-asset corporates - e.g. Rio Tinto or BHP Billiton - can attract debt at Holdco level, namely bonds or bank debt; and with it fund new projects. This may be called 100% debt funded, but it is actually 100% equity from a asset level perspective (corporate funds put at work). If a project is financed standalone, as displayed in Figure 3.4, there will be a minimum equity requirement.

## 3.3 Bank portfolio, risk management, and stress-testing

For most commercial banks, lending is their primary business. The loan portfolio is usually the most valuable asset and the primary source of income. As a result, it is one of the most significant threats to a bank's safety and soundness. Loan portfolio issues have historically been the leading source of bank losses and collapses, whether owing to inadequate credit standards, poor portfolio risk management, or economic downturn.

Effective credit portfolio and credit function management are critical to the security and integrity of the bank. Loan Portfolio Management (LPM) is a way to manage and control the risks inherent in the credit process. LPM assessment includes an analysis of the steps bank management needs to take to identify and manage risk throughout the lending process. The assessment focuses on what management is doing to identify the problem before it occurs.

An example of this is the bank's portfolio in the current study. From figure 3.5 it can be observed how its exposure is balanced into different risk. Moreover, companies in this case are partially measured by the X-axis. Furthermore, Debt to EBITDA ratio provides information to the bank about the creditworthiness of each of their current or potential clients. In fact, in the covenants for business loans, banks frequently specify a debt/EBITDA goal, which a firm must meet or face having the whole loan become due immediately. Credit rating agencies frequently use this statistic to analyze a company's likelihood of defaulting on issued debt, and companies with a high debt/EBITDA ratio may be unable to pay their debt properly, resulting in a negative credit rating (Kenton, 2020). Commonly, banks provide loans to companies up to x2.5 of this ratio. However, we see that a particular client is beyond this threshold, possibly as a result of changes in its financial situation compared to when the loan was given. In these cases, banks usually intervene on the finances of the client and propose actions to reverse this situation and avoid default.

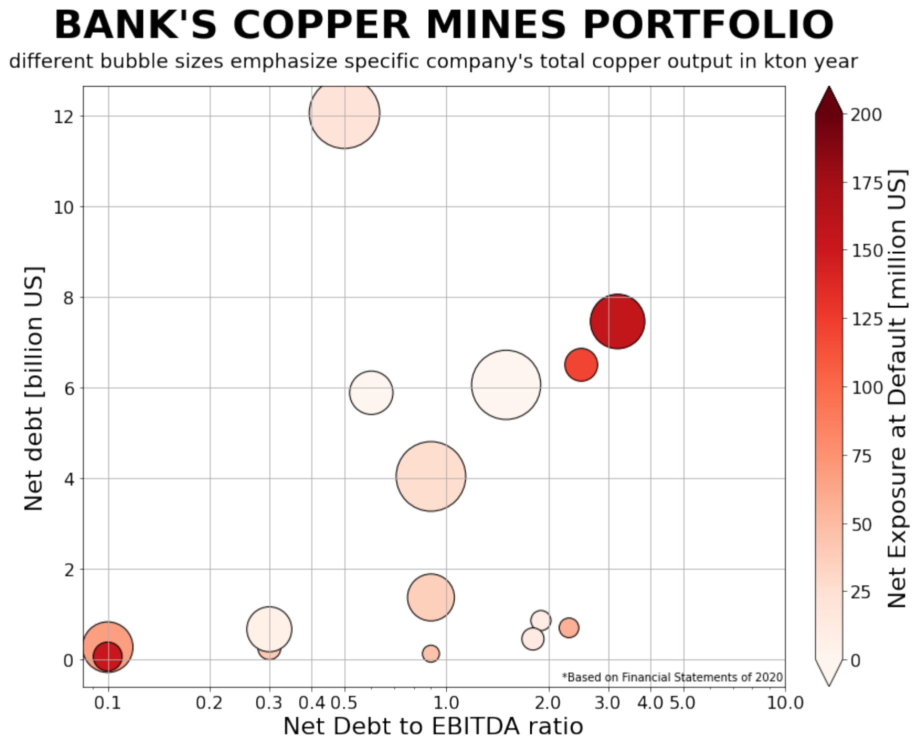


Figure 3.5: Company size, leverage level, and the bank's exposure at default for each company in its copper mine portfolio - only loans with maturity over year 2025 were taken into account. Own elaboration based on the financial statements of individual mining companies and the bank internal data.

Alternatively, corporate debt is usually diversified into bank syndicates. Figure 3.5, displays the total net debt as well as the bank net exposure of the total debt for each company and asset. In this case, net debt indicates how much debt a corporation has on its balance sheet in comparison to liquid assets. Net debt represents, in other words, the amount of debt left after substracting cash balance from gross debt. The formula is described by Murphy (2020) as the following:

$$NetDebt = STD + LTD - CCE$$

Where: STD is debt that is due in 12 months or less and can include short-term bank loans, accounts payable, and lease payments; LTD refers to Long-term debt, and is debt that with a maturity date longer than one year and include bonds, lease payments, term loans, small and notes payable; finally CCE stands for Cash and liquid instruments that can be easily converted to cash. On the other hand, exposure at default or EAD, is defined by Tarver (2020) as the total value of a bank's exposure when a loan defaults. Whereas, net exposure at default discounts insurance coverage, for which this amount stands exclusively for the real amount that the bank would be exposed to in case of default.

On this matter, the OCC (1998) distinguish 9 different elements:

1. Assessment of the credit culture,
2. Portfolio objectives and risk tolerance limits,
3. Management information systems,
4. Portfolio segmentation and risk diversification objectives,
5. Analysis of loans originated by other lenders,
6. Aggregate policy and underwriting exception systems,
7. Stress testing portfolios,
8. Independent and effective control functions,
9. Analysis of portfolio risk/reward tradeoffs

For this particular study, we will be focusing on element 7, testing in particular climate change risks on the bank's portfolio. A bank does stress testing to examine the possible impact on the performance of a loan, concentration, or portfolio segment by changing assumptions about one or more financial, structural, or economic variables. This can be achieved by "back of the envelope" analysis or through the use of complex financial models. The issue is not the approach used; rather, the issue is asking the essential "what if" question and incorporating the subsequent answers into the risk management process. Stress testing is a risk management concept, and regardless of the sophistication of their methodologies, all banks will benefit from implementing this risk management concept to their loans and portfolios. In this case, stress testing is employed to estimate their exposure to interest rate fluctuations by subjecting various assets and liabilities to hypothetical "rate shock" scenarios.

After conducting a stress-test, the bank might change financial factors and analyse the impact as part of the initial or continuing credit review. These findings can then be extrapolated to the portfolio level in order to analyze the influence on portfolio credit quality.

## 3.4 Cash flows

So far, it was discussed previously in this chapter about mines' capital structure decision drivers, followed by deep diving into debt financing options, and the banks' instruments in this regard. Furthermore, on the banks' side, we had an overview of how they manage their portfolios and preview potential risks and exposures through financial modelling and stress-testing. Some take-aways are the banks' interest in the clients liquidity and short-term capability to pay debt, but also their current outstanding debt related to this capability.

In this section we will review and compare between companies the components of this capability, which in other words, are the elements that comprise the companies' EBITDA.

### 3.4.1 Revenues

Usually, real revenues can suffer great fluctuations due to the nature of the commodity market. Wherein unexpected demand spikes are met with delayed supply responses due to the complicated production processes of copper - as it is the case with most of commodities - bringing price fluctuations with long durations of upturns and downtrends. This together composes the main reason for copper supercycles.

Additionally, copper prices are one of the most relevant drivers for stock piling and blending ores, which in the short term also affects the mine's revenues. In particular, among porphyry deposits, the copper grade varies. Premature access to higher-grade material minimizes the time it takes to pay off the capital expenditure and hence improves profitability. The presence of recoverable concentrations of additional elements (such as Mo, Au, and Ag) also enhances income. Many porphyry deposits include substantial low-grade halos (0.2 percent Cu), which might be economically viable if Cu prices rise, especially after infrastructure is in place and capital expenses are paid off. Arndt et al. (2017) mentions that often this material is kept in low-grade stockpiles at some mines during stripping in order to reach material with higher commercial grades. Low-grade stocks are a limited but easily accessible future resource.

There is a relationship between the price of copper and the miners cost curve percentile. An analysis was carried out (see Figure 3.6), by comparing the closing average price of copper with the costcurve percentiles for each year in a timeframe from 2010 to 2021. The results showed that commonly the average closing price of copper lays within the **98.7%** percentile of the copper primary producers supply cost curve. In other words, if the supplier in the 98.7% percentile produces copper at 180 cents per pound, this analysis assumes the price will be then 180 cents per pound. This value is relevant as it will be used as a reference to predict copper price in the model in the following chapters.

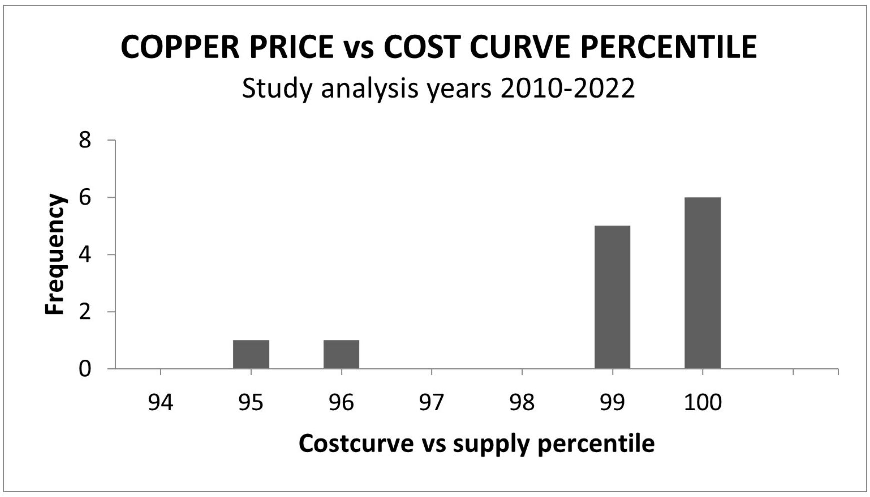


Figure 3.6: Copper price versus costcurve supply percentile, mean (98.70), median (98.86) . Own elaboration adjusted from S&P Global IQ database.

### 3.4.2 Cash-costs

For convenience, cashcosts have been classified in this thesis from a accountable point of view rather than from a processing one. This is: labor, energy, reagents, others, and royalties. This is mainly due to the fact that - as we will see later - most of the climate scenario inputs can be worked directly or closely with these costs, as a relationship can be observed.

Figure 3.7 shows the copper primary producers costcurve. Each producer is placed in order of cost from the least to highest, and the width represents its particular copper output to the whole copper supply. Major players like Escondida, Grasberg, Collahuasi, among others have been highlighted.

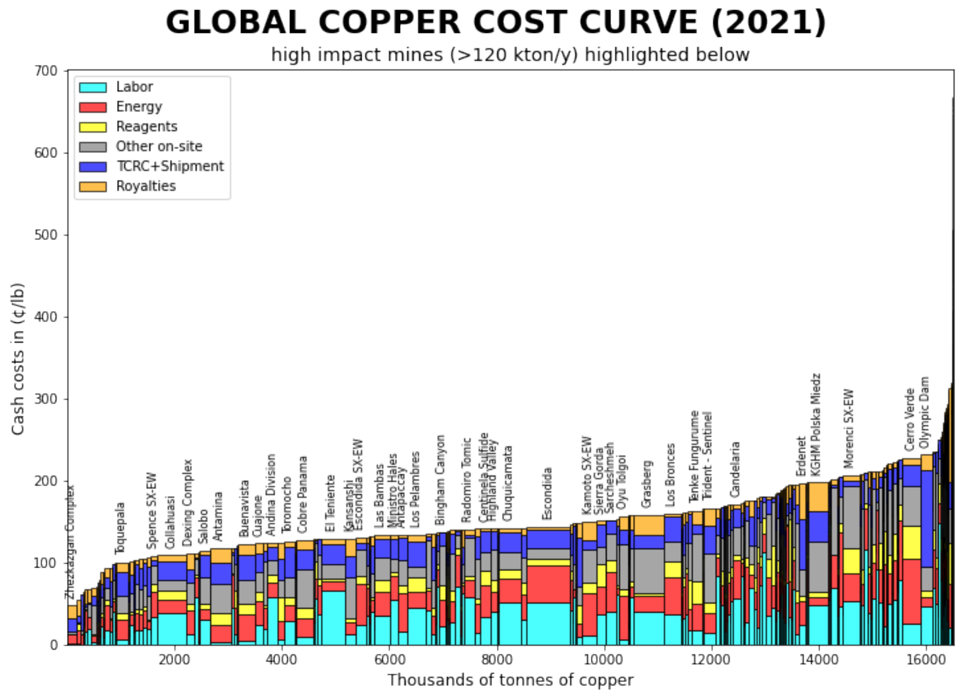


Figure 3.7: Global cost curve for copper mines . Own elaboration adjusted from S&P Global IQ database.

From this figure, it can be noted that most competitive mines are placed on the left side of the curve. Likewise, the more on the left, or in other words, the more competitive the producing costs are, the less sensitive to price fluctuations that specific mine is. While mines on the right side are as consequence the least competitive ones, which also denotes their high exposure to price fluctuations, which can eventually put on hold their operations when it goes lower than the break-even point in where they profit. Therefore, this curve is useful to analyze the whole copper supply market competitiveness and risk. Hence, this same curve will again be analyzed once climate risks associated costs are plugged into each specific mine and then these results will be discussed later.

For now, it can be noted that the costs of the mines that contribute to the 79.3% of the total supply ranges from 100 to 200 cents per pound. The whole copper mines cost structure is mainly composed by three components: labour (26%), other costs (23%), and energy (21%). Alternatively, figure 3.8 provides an overview of cashcosts from a country level.

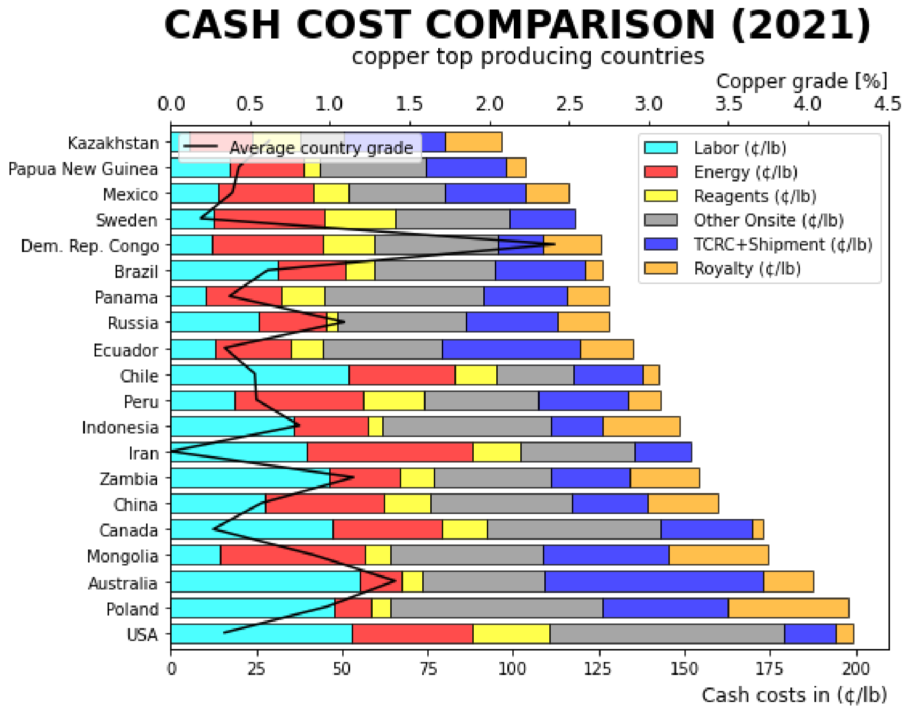


Figure 3.8: Weighted average cash-cost distribution for top copper producing countries. Own elaboration from S&P Global IQ database.

This particular figure provides a general indication of the cost structure of copper main producers. Considerable differences can be observed between countries where some cost components play a big role on the whole, which is also a common factor among neighbor, similarly-developed, or culturally-alike countries. For instance, Canada and the US share quite a comparable cost structure where energy and labour are the biggest components. Likewise, countries in Africa and Asia are prone to have lower wages and thus labour costs are less relevant. Moreover, isolated countries, such as Australia, present as a consequence considerable shipping costs compared to other countries.

Generally speaking, from the results shown in Figure 3.8, there seem to be no correlation between the copper grade and the total costs. However, it seems that there is indeed a correlation for energy and reagents overall costs. Nevertheless, this can be better analyzed if these costs are broken down into different mine types, i.e. open-pit, underground, and mixed mines. This breakdown can be found in the Appendix.

When comparing mining methods, main differences can be seen firstly on overall grades. Since underground mining is a selective mining method, overall grades are consequently 2.2 times higher than in open-pit. This fact has several implications in the cost structure. Firstly, more waste has to be mined

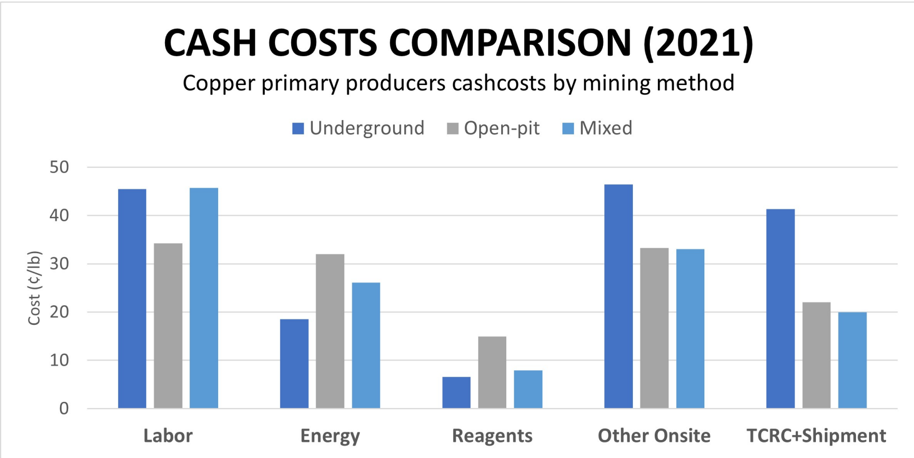


Figure 3.9: Cash-cost comparison by mining method for primary copper producing countries. Own elaboration from S&P Global IQ and CRU Global database.

and hauled, increasing the overall costs on energy for open pit mines by 72% compared to underground. Moreover, given the fact for open pit mines more material has to be processed to produce the same amount of copper, processing costs increase as well, as more reagents and water are required. For this reason, underground reagents costs are just a 43% of open-pit's reagents costs. Finally, due to massive scale of open pit mines, often more personnel is required increasing the global labour costs, but however decreasing the unit costs due to economies of scale. This results in open-pit mines' labour costs being 75% of underground mines'. However, as discussed previously, open-pit mining is preferred due to its simplicity and lower capital costs when compared to underground mining.

The following subsections will discuss about the main drivers and trends of each of these costs components as they will be conveniently used for the stress-test model afterwards.

### Labour

These costs include wages attributable to mining, including all salary and oncosts. Darling (2011) defines labour costs as the result of multiplying the number of workers assigned to any one discipline by the number of hours worked per shift and then multiplying the result by the associated hourly wage for the region in which the mining project is located. Nonetheless, the author notes that a case can be made that labour efficiency is proportional to wage rates, so that more people are required to achieve the same result in lower-wage environments. Consequently, lower wage rates rarely result in proportionally lower operating costs. Wages must be factored for the additional expenses incurred by the employer for each employee. These expenses - commonly referred to as burden - include contributions to Social Security taxes, worker's compensation and unemployment insurance, retirement plans, and medical benefit packages. Additionally, evaluators must factor either the wages or the work force to account for the expenses associated with vacation and sick leave, shift differential allowances, and overtime pay.

### Energy

Energy costs are a significant proportion of total cost inputs for the global mining industry, and with time these costs are becoming more relevant. Smith (2013) mentions energy price increases are already a considerable operating expense for most large mining businesses, accounting for 7-12% of overall costs, but increasing at a rate of 6% per year. Furthermore, underground mining operations are getting more energy intensive as surface ore deposits become more difficult to find and the requirement for more and deeper underground operations increases. Direct energy accounts for fuels burnt on-site while indirect energy accounts for energy - typically electricity - used on-site or purchased from national grid, but generally produced off-site. Many factors contribute to variability between sites for the production of copper. This is due to a variety of factors such as mine depth, smaller ore throughputs, and the need for support services such as ventilation.

Northey et al. (2013) examined the correlation between ore grade and energy consumption (see figure 3.10). These findings reveal that the consumption of diesel in the mine site increases with declining ore grade due to the need to process more ore per unit of copper.

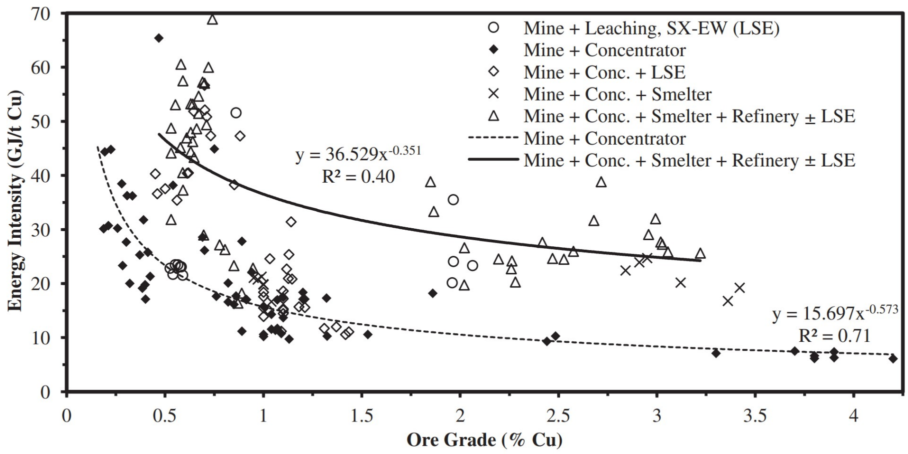


Figure 3.10: Energy intensity as a function of ore grade for 31 copper operations, with each data point representing a year of production. From Northey et al. (2013).

Figure 3.11 provides an overview of how energy is consumed by the different units for both underground and open-pit mines. The evidence displayed shows similar energy-use structure, where the 80/20 of the total usage is composed from three main activities. For both cases, roughly half of the total consumption is employed for beneficiation or concentration processes - from which a big share is normally used for crushing and grinding. Particularly, Northey et al. (2013) explains that lower ore grades increase the energy requirements for beneficiation as more ore has to be treated to produce the same amount of copper concentrate. Even for a specific ore grade, large variability exists in the energy consumed at this stage of copper production. Communition and flotation circuits vary between mine sites due to different ore mineralogy and hardness. Differences such as the effect of grind size on the energy intensity are amplified as ore grade declines. Therefore improvements in grinding efficiency and optimisation of grind size have potential for significant energy reductions in the future. However, offsetting this is the possibility that future ore deposits may be finer-grained and will require grinding to finer sizes. The second highest energy intensive activity position belongs to mining, where loading and hauling are primarily the high-energy-intensive activities. Likewise, when ore grades decline, more material has to be mined and handled, which increase the energy consumption accordingly. The last is downstream processing, being pyrometallurgy, the major activity responsible of this consumption. Once a concentrate has been produced, the energy requirements of the smelting and refining stages are dependent on the composition of the concentrate, but not on the original ore grade.

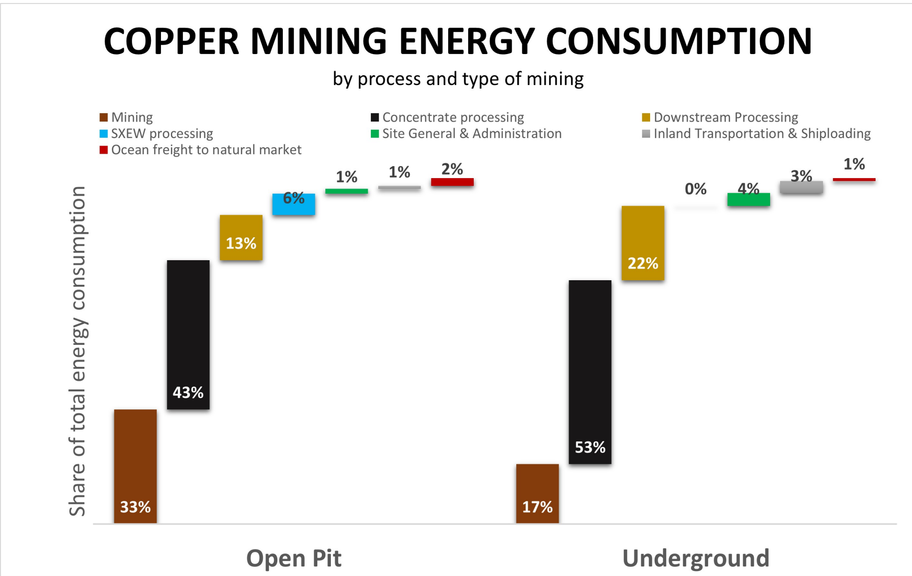


Figure 3.11: Energy consumption based on carbon dioxide emissions for open-pit and underground mining. Own elaboration from CRU Global database.

### Reagents

Reagents play a key role controlling the efficiency or performance of flotation beneficiation. Shen (2016) describes flotation as a complex process where mineral particles are mixed, suspended by strong agitation, and separated by attaching to air bubbles selectively. Surface property is the determinant factor as only hydrophobic particles can adsorb on bubbles which lift them to the top of flotation cell, leaving the hydrophilic gangue minerals at the bottom. Reagents are usually added to selectively render the valuable minerals to become hydrophobic. As a consequence, a great amount of reagents are used annually into the flotation process, hence, playing a big role in the mine's budget.

In the case of copper sulphide ores, the increasing scale of ore extraction and processing due to decreasing average copper ore grade as well as complexity, determines high requirements of these reagents, and consequently, high costs - e.g. if 80,000 tonnes/day milled ore are processed by froth flotation, the cost of chemical reagents per day is about USD 12,000 (Reyes-Bozo et al., 2014). Moreover, as mentioned before, due to the decrease of copper ore grades over time, greater consumption of water and energy, but also chemical reagents is required to efficiently carry out processing, particularly the consumption of collectors, frothers, and modifiers in froth flotation.

### Other on-site

This category includes, based on S&P-Global (2021b) methodology, all other costs for the mining operation - with the largest portion commonly being explosives and third party site services such as geological services, among others such as grinding media, activated carbon, other third party site services, insurances, maintenance, etc. Likewise, these costs will be also consequently increased by lowering ore grades. However, the data used in this thesis considers the increments already. Nevertheless, it is relevant to remark that later on in this thesis, costs associated to insurances adjusted premiums will be considered as main impact due to physical climate risks.

### Royalties

In different countries, royalties may be assessed based on volume, value at various points along the value chain, or profit/rent. Lilford and Guj (2020) describes three main types of mining royalties:

1. **Net smelter return (NSR):** based on the % of the net proceeds received from the smelter. The revenues of the sale of the mineral product to the treatment facility are used to determine a smelter's returns net royalty, which can be paid in cash or in substance. Costs incurred before the commodity is sold and after it leaves the mining property, such as transportation, insurance or security, penalties, sample and assaying, refining and smelting, and marketing, may be deducted.

2. **Net profits interest royalty (NPI):** this is a profit based royalty as it is based on % of the net profit generated by the mine. A royalty based on net profits is calculated by taking a fixed percentage of the income from a mine-mill complex and subtracting the costs of production. Frequently,

the NPI is not paid until the project's capital investment and all pre-production expenditures have been recovered.

3. **Gross overriding royalty (GOR):** also known as production royalties, comprises a fixed payment per tonne. Furthermore, the owner is allowed to a portion of the market price of the mined product at the time it is ready for purchase, less any expenses spent by the operator to transport the commodity to the point of sale. The cost of making the items saleable and transporting them to market are included in these deductions.

Otto et al. (2006) notes how mineral royalties seem to have the potential to undermine political stability - as when they increase costs this usually leads to layoffs, causing financial pain for affected areas and, eventually, an increase in poverty levels in mineral-dependent countries. The intentions of politicians charged with managing the country's mineral resources are more likely to be questioned in impoverished countries. Public dissatisfaction may evolve into political unrest if governments are unable to establish mechanisms to modify the situation at the grassroots level.

Finally, some countries - as mentioned before in the Political Risks section - intend to increase royalties due to social demands and post-COVID19 recessions as an intent to finance their agenda. This certainly poses a risk for the mining industry, however, this is beyond the scope of this work and the different scenarios regarding this matter will not be studied.

# Chapter 4

# Climate risks and copper mining

### Introduction

There is no doubt that global warming is occurring, bringing with it extreme events and permanent shifts. Whilst scientists are unsure about exactly how and which physical and transition risks will manifest, it is known that some variety of those risks will be encountered. Furthermore, the corresponding human reactions that are taken in present time towards it will have deep consequences, both in scope and magnitude, for economic and financial institutions.

On the other hand, mining is intrinsically dependent on the natural environment, and the industry's long-term survival. This is due its dependence to a number of favorable natural circumstances, including, but not limited to, a habitable climate, access to water supplies, and supporting infrastructure. Hence strategic decision-making about mining operations is inextricably linked to the location of the deposit. Consequently, operations cannot be relocated if natural environmental circumstances become unfavorable for different reasons. Moreover, the mining industry is facing energy, legislation and carbon risks – so called transitions risks – in addition to the previously mentioned harsh weather-related concerns. These mainly concern the risks related to diesel fuel costs and market-based carbon pricing. As a result, mining industry is vulnerable to climate change.

Since climatic risks are highly sensitive to localities, six different copper mining regions were defined and will be studied in depth in the first section of this chapter. Moreover, previously in Chapter 1 climate risks were briefly discussed. In this chapter, both, physical and transitional risks related to climate change will be studied in depth for all the defined copper producing regions.

## 4.1 Climate scenarios

### 4.1.1 Overview

For non-experts, climate modelling is a technical and complex field. Additionally, the absence of a defined analytical framework for converting climate forecasts into macro-financial assessment hampers institutional implementation. As a result, the Network for Greening the Financial System, or NGFS, has formulated a series of Reference Scenarios as well as a Guide on how to undertake scenario analysis. The scenario analysis technique enables institutions to investigate vulnerabilities and repercussions along a variety of conceivable routes.

NGFS has four different climate scenarios illustrated by Figure 4.1:

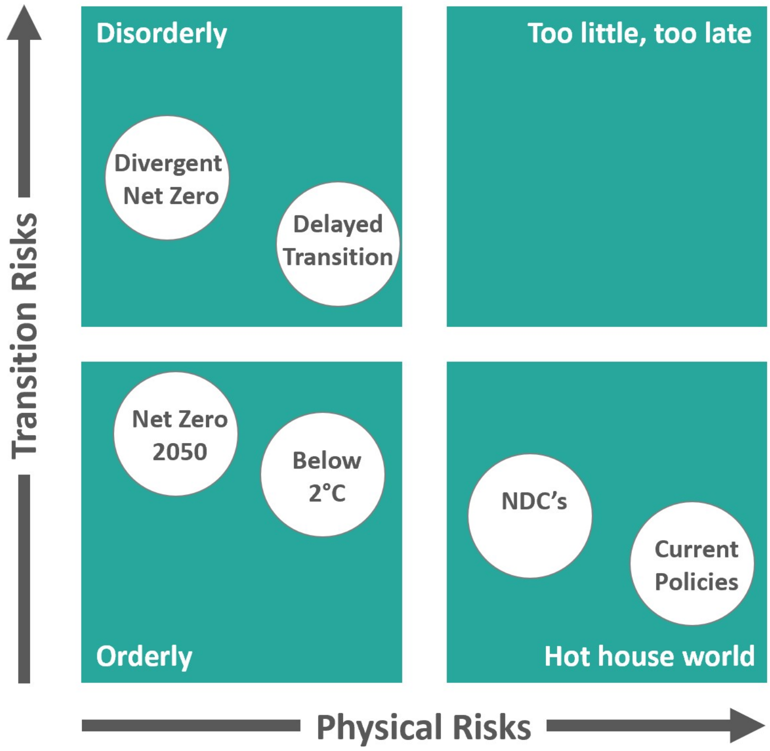


Figure 4.1: NGFS climate scenarios. Own elaboration adjusted from Elderson and Breeden (2020).

These scenarios are described below based in official NGFS documentation provided by Elderson and Breeden (2020):

**Orderly**

The two climate scenarios within this block stand over the assumption that climate measures are enforced early and become increasingly severe over time. Physical and transition risks are both quite mild. The usual gradual transition scenario anticipates swift action to reduce GHG in conformity with the Paris Agreement. It also plans to establish an early carbon tax that would increase slowly each year, with the aim of maintaining global warming far under 2°C. It also considers that carbon dioxide removal (CDR) technologies are completely developed. This results into attaining net zero $CO_2$ emissions between 2050 and 2070. Physical and transition risks are projected to be limited throughout the duration since policy measures are executed early and progressively.

- **Net Zero 2050** is an aggressive scenario in which global warming is limited to 1.5°C by rigorous climate legislation and innovation, with net zero $CO_2$ emissions by 2050. By this time the United States, Japan and countries within the European Union will have achieved net zero emissions for all greenhouse gases. This scenario implies that strong climate policies are implemented immediately. CDR is used to promote carbon reduction whilst keeping emissions low and roughly in line with healthy levels of bioenergy production. Physical risks are minor, but the transition risks are significant in this scenario.
- **Below 2°C** this scenario gradually tightens climate regulations and assumes that climate laws are implemented immediately and progressively become more rigorous, albeit not to the same extent as in Net-zero 2050. The deployment of CDR is limited. Physical and transitional risks are both low.

**Disorderly**

Larger transition risk is explored in disorderly scenarios due to policy delays or divergence across nations and sectors. For a given temperature outcome, carbon costs are often greater. The typical scenario for a disorderly transition depicts a significantly more difficult route to achieving the Paris Agreement objectives. Realising that all these initiatives will not be sufficient to achieve pledges, the carbon price is adjusted much higher beyond 2030. The scenario also implies that only a limited amount of CDR technologies would be accessible. Because of the time lag, net zero $CO_2$ emissions must be achieved sooner, by roughly 2050. Similarly, the annual growth in carbon pricing is substantially faster, at \$35/tonne $CO_2$.

- **Divergent Net Zero** this scenario achieves net-zero emissions by 2050, but at a greater expense due to desynchronized initiatives adopted within industries and a faster transition of fossil fuels. This is comparable to a situation in which a failure to synchronize government consistency across sectors results in a massive responsibility on individuals, yet decarbonization of energy supply and industry is less severe. Generally, it differs from

Net Zero 2050 in that it assumes stricter environmental regulations in the automotive and construction sectors as well as less availability of CDR technology. This results in much greater transition risks than Net-zero 2050, but the lowest total physical risks among the six NGFS scenarios.

- **Delayed Transition** Delayed Transition assumes global annual emissions do not decrease until 2030. Strong policies are then needed to limit warming to below 2°C. Negative emissions are limited. This scenario assumes new climate policies are not introduced until 2030 and the level of action differs across countries and regions based on currently implemented policies, leading to a “fossil recovery” out of the economic crisis brought about by COVID-19. The availability of CDR technologies is assumed to be low pushing carbon prices higher than in Net Zero 2050. As a result, emissions exceed the carbon budget temporarily and decline more rapidly after 2030 to ensure limiting global warming to below 2°C. This leads to both higher transition and physical risks than the Net Zero 2050 and Below 2°C scenarios.

#### Hot house world

These scenarios presume that certain climate measures are put in place in some countries, but worldwide efforts are insufficient to prevent major global warming. Critical temperature limits are breached, resulting in serious physical risks and permanent consequences e.g.: sea-level rise. As an outcome, the Paris Agreement’s climate targets are not achieved, posing significant physical risks in the mid to long term. This is a projection of what might occur if no further precautions were implemented. As a result, the change in carbon pricing is estimated to be insignificant.

- **Nationally Determined Contributions** All committed policies, even those that have not yet been implemented, are included in NDCs. This scenario assumes that the mild and diversified climate ambition reflected in the NDCs at the start of 2021 will be maintained throughout the twenty-first century (low transition risks). Emissions are declining, but lead is still linked with moderate to severe bodily hazards; this is marginally lower than in the Current Policies scenario, but still far above the Paris target. Transition risks are quite low when all committed but not yet executed policy initiatives are included.

- **Current Policies** the hypothesis of this scenario implies that only current in existence regulations are continued, resulting in severe physical risks as greenhouse gas emissions continue. Furthermore, this scenario can allow central banks and regulators look at the long physical risks to the financial and economic system if we stay on our current path to a ”hot house world.”

#### Too little, too late

The hypothesis for this scenario is that a potential late transition would strive to limit physical risks. Although no scenarios have been developed particularly for this use, this domain can be studied by presuming increased physical risk consequences for disorderly scenarios.

### 4.1.2 Key assumptions and sensitivities

Assumptions related to transition risks involve three major areas: the speed and timing regulations take place as well as the kind of policy to be undertaken; the progress in emission reduction and carbon capture and storage technologies; and behavioural shifts in companies and consumers. Sensitivities of the model have to do mainly to assumptions related to economic-financial response under each scenario. Some of them include the demand and supply balance of goods in the short and long run; investment levels; the role of the financial sector in allocating the required capital or not; and monetary policy responses. Transition can be for some scenarios a decrease of growth, whereas for other ones they can produce green growth effect.

In the case of physical risks, Elderson and Breeden (2020) mentions "great level of uncertainty around the current estimates of economic damages that result from climate change". Moreover, damages linked to climate physical risks have been estimated through expert judgement and impact assessments. Due to the lack of empirical foundations for the model, experts believe that financial damages are likely to be underestimated in these models. Even through recent developments in empirical analyses, high-level estimates of economic repercussions may still be generated on a regular basis. This is linked to an insufficiency of granular data, ambiguity about the core biophysical processes, and ignorance about the extent of response in the long term.

### 4.1.3 Scenario selection

From the above described scenarios, three scenarios have been chosen to be used to stress-test copper mines:

- Net Zero 2050
- Delayed transition
- Current policies

Each of them contained within the three blocks, which will provide a broad outlook after running the model, given their significant differences. However the main reason for their selection is due to their availability in regards to climate data in the NGFS database.

## 4.2 Physical risks

Physical risks, related to higher frequency and intensity of extreme weather occurrences, are expected to have significant consequences in macroeconomics. In this regard, from an more general perspective, Elderson and Breeden (2020) notes three major points to be affected by these risks i.e.: people, physical capital, and natural capital. The first comprises labour productivity, mortality and leisure as main aspects. The second, is related to the required reinvestment to repair damages of property and infrastructure due to severe climate events e.g.: floods, windstorms, etc. The third and last refers to negative shifts in ecosystems and agriculture which will have significant consequences in local economies.

Northey et al. (2017) mentions considerable changes in climate are projected for regions containing 27-32% of global copper resources. Moreover, Ruttinger and Sharma (2016) notes climate change will have both direct - i.e. operational and performance-based - and indirect - supply security and growing energy prices - effects on the mining industry. Water-related consequences, namely, droughts, floods, cyclones, and storms; heat-related impacts such as bush fires and heat strokes; and sea level rise are among them. A combination of these effects may jeopardize the sector's viability by denying the industry – and its personnel – a safe operating landscape, both spatially (impacts felt across the immediate vicinity of the mining site and areas further downstream) and temporally (impacts felt across the immediate vicinity of the mining site and areas further downstream) (including, sporadic short-term and more permanent chronic changes). Additionally, some of the world's largest mining operations are also located in remote, climate-sensitive areas (for example, Mongolia's Gobi Desert, Chile's Atacama Desert, Western Australia, and Canada's North and Arctic).

From the above mentioned climate effects on mining, Delevingne et al. (2020) highlights and studied the three most relevant ones:

### 4.2.1 Water stress

Water is widely used in different processes along mining operations. Some of the most significant include mineral processing and dust suppression. The requirements of this resource also will depend on different factors like the local climate, ore mineralogy and grade, the scale of infrastructure and ore processing, and the extent of tailings dewatering and water recycling (Northey et al., 2017). Figure 4.2 illustrates the water footprint in both copper production processes i.e.: pyrometallurgy (mining, concentration, smelting and refining) and hydrometallurgy (mining, heap leaching and solvent extraction-electrowinning):

Northey et al. (2014) estimated the average water use for the processes mentioned based on a water mass balance. For the hydrometallurgical processes, the sulphuric acid consumption is the major component of indirect water requirements. Surprisingly, the little amount of sodium cyanide supposed to be employed as a depressant in the flotation stage - typically classified as one of the reagents - was found to actually be a considerable source of indirect water consumption for the copper pyrometallurgical process. Figure 4.3 provides an outlook of the water consumption for both mentioned processes:

The data displayed figure 4.3 shows that the main sources of input for water

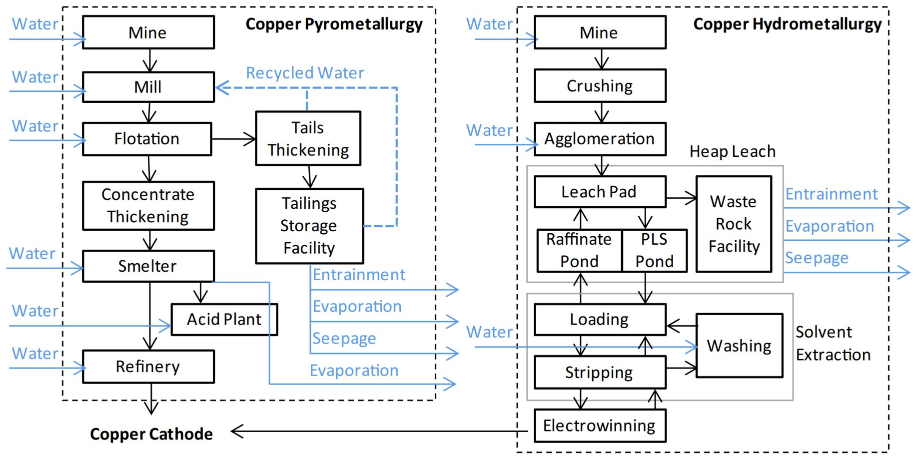


Figure 4.2: Major water flows for two simplified copper production processes. From Northey et al. (2014)

| | Copper | |
|---|---|---|
| | Pyrometallurgy $m^3$/t Cu | Hydrometallurgy $m^3$/t Cu |
| *Inputs* | | |
| Groundwater | | |
| – Mine dewatering | 21.6 | 31.1 |
| – Ore entrainment | 2.94 | 4.24 |
| – Borefields | 79.2 | 41.9 |
| Total | 103.7 | 77.2 |
| *Outputs* | | |
| TSF/Heaps | | |
| – Entrainment | 59.9 | 36.4 |
| – Evaporation | 19.6 | 11.9 |
| – Seepage to groundwater | 12.7 | 7.7 |
| Task losses | 11.6 | 21.2 |
| Total | 103.7 | 77.2 |
| *Consumption* | | |
| Groundwater | 91 | 69.5 |
| – Per tonne of ore | 0.62 | 0.32 |

Figure 4.3: Overall water inputs, outputs and consumption for the metal production processes (rounded to three significant figures). From Northey et al. (2014)

are borefields and the dewatering of the mine for both of the processes, being Pyrometallurgy overall roughly a 34% more water intensive. On the other hand, figure 4.2 showed previously that the smelter and tailings storage facility for pyrometallurgy are hot spots of water output, whereas for hydrometallurgy this is the waste rock facility. Based on the data presented, entrainment is the major cause of water output from the closed circuit, followed by evaporation and seepage to ground water. However, Northey et al. (2014) has classified the difference of the input and output water as output "task losses", which surprisingly for hydrometallurgy this is quite substantive reaching a 27.4%.

Climate change is expected to cause more frequent droughts and floods, altering the supply of water to mining sites and disrupting operations. Delevingne et al. (2020) found that today, 30 to 50 percent of production of these four commodities is concentrated in areas where water stress is already high clustered into seven water-stress hot spots for mining:

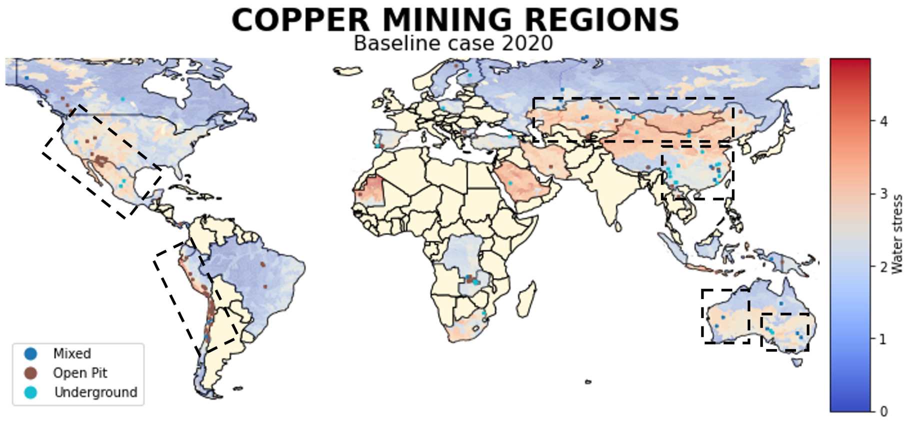


Figure 4.4: Global copper mining and water-stress hot spots: Central and East Asia, the Chilean coast, eastern and western Australia, and a large zone in western North America. Own elaboration adjusted from Gassert et al. (2013)

Delevingne et al. (2020) predicts that these hot spots will worsen in the coming decades. In Chile, 80 percent of copper production is already located in extremely high water-stressed and arid areas; by 2040, it will be 100 percent. Mining regions not accustomed to water stress are projected to become increasingly vulnerable. By 2040, 6 percent of copper production could shift from high to extremely high water stress. Depending on the water intensiveness of the processing approach, such changes, while seemingly minor in percentage terms, could be critical to a mine's operations or license to operate.

The ratio between total water usage and water availability is frequently defined as the water stress index, or WSI. The closer water usage is near water supply limits, the more probable natural and human ecosystems may be stressed. Figure 4.5 shows that a considerable share of the total copper output is located in water stressed countries, with a WSI weighted average of 0.5. This is considerable high when compared with other commodities such as Nickel (0.24) or Gold (0.4) (Northey et al., 2014).

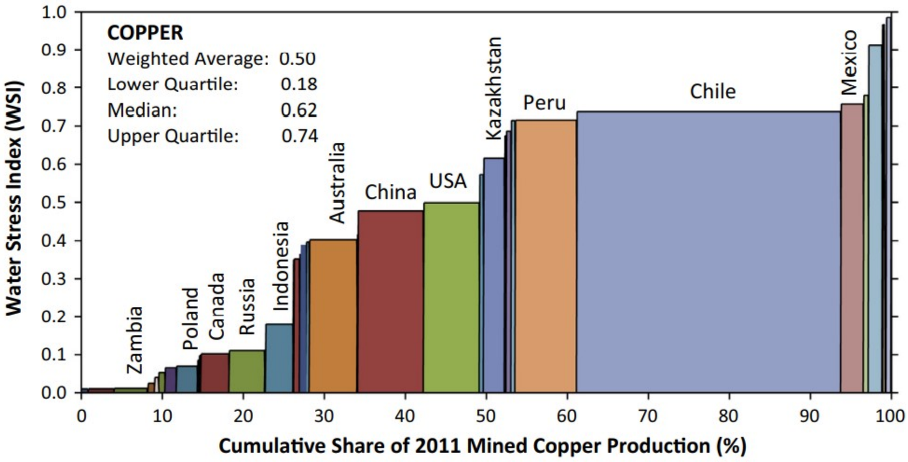


Figure 4.5: Water stress index versus mined production for copper. From Northey et al. (2014).

Changes in water supply caused by climate change may lower the quantity of water available for mining, processing, and refining industries in many regions of the world. These changes, according to Smith (2013), may lead to increasing competition for water resources, threatening community relations. Mining executives in these regions are acutely aware of the water issue. For instance, Leagold Mining recently shut down its RDM gold mine in Brazil for two months because of drought conditions, even though it had built a dam and a water pipeline (Jamasmie, 2018). Since water stress is likely to increase at different rates from place to place, mining executives will need to look at local water-stress projections for their individual sites and determine where the worst effects are likely to occur.

### Desalination

Alternatively, the increase of water usage, due to lower grades (see figure 4.6, combined with water scarcity in some regions is forcing some mines to opt for alternative sources of water as legislation towards water management becomes more strict. Currently, desalinization of sea water has been the preferred option for most mines, where reverse osmosis process is the most widely used. A good example is Chile's mining activity, which faces a restrictive water supply scenario. The water shortage is mainly in the northern part of the country, an area where mining activity is concentrated. As a result, the use of seawater was no longer seen as just an alternative and was now needed to ensure production. For this reason, the extraction of seawater increased significantly, to the point that during the period 2009-2016 it went from 0.32 to 2.45 m3/sec, equivalent to a 666% increase (Garcia, 2017).

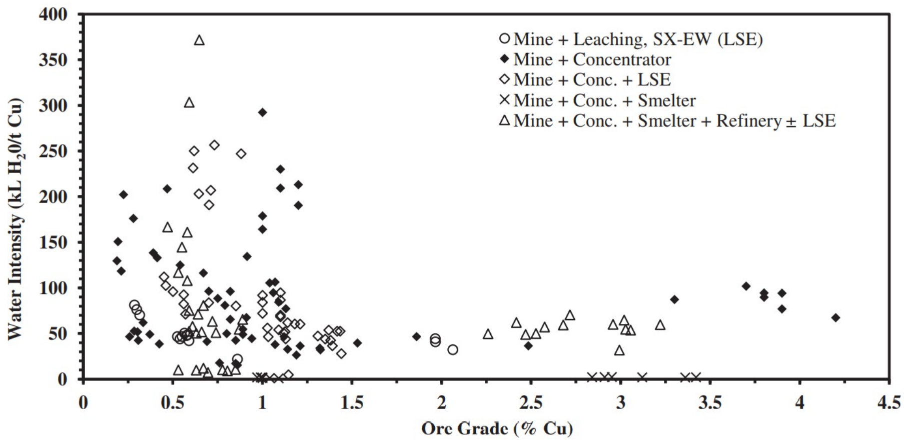


Figure 4.6: Water intensity as a function of ore grade for 31 copper producing operations. From Northey et al. (2013).

The energy consumption of seawater desalination (by reverse osmosis) is considerable, and depending on the treatment capacity of the desalination plant, would have a total cost of between 0.6 and 1.2 US$/m3. Mines on average pay US$5 per cubic metre of desalinated seawater put into the mine, while the same unit of fresh water cost US$1.6. Unsurprisingly, the cubic metre of desalinated water costs less if it is on the coast (USD 1), and rises as it is pumped inland. In high altitude areas, where there are several mining companies, it can cost between US$ 8 and US$ 10 /m3. However, in the future, technological advances are expected to reduce the cost of desalinated water by 20 percent over the next five years and 60 percent over the next 20 years (Garcia, 2017). Miners, on the other hand, are aware that allocating resources will also enable improved community involvement and water distribution to those most affected by shortage, potentially easing opposition to new mining projects.

Figure 4.7 shows the result of the studies carried out by Brychcy et al. (2020). The author estimates that desalination-based mines are predicted to account for 62% of Chilean production by 2028. The remaining 38% intend to use continental water, with the majority of it (68%) coming from mining. The figure also shows that seawater could be up to 4-6 times more costly than business as usual, whereas desalination can reach 8-10 times. These aggressive cost increases could potentially delay transition from mining into more sustainable sources of water.

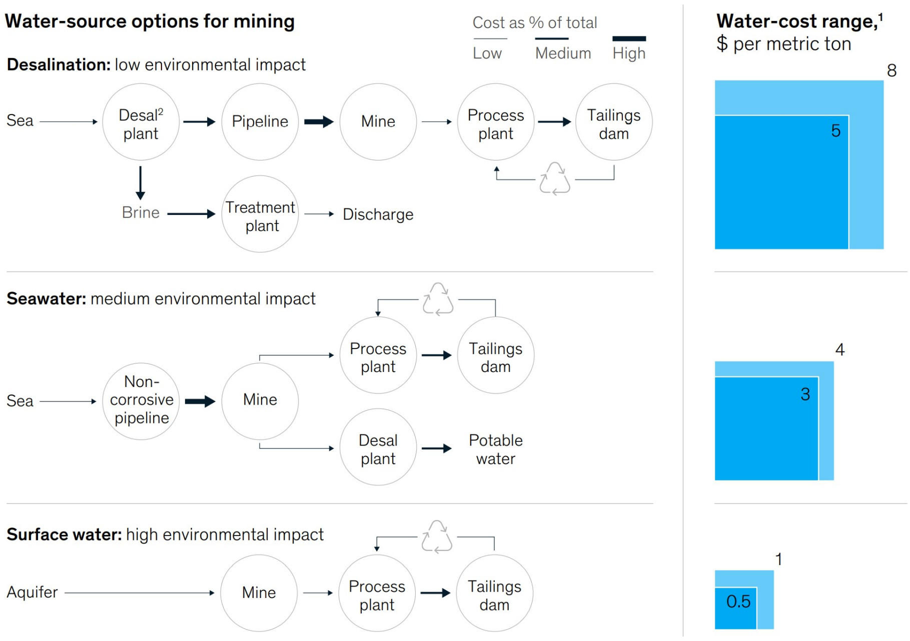


Figure 4.7: Water-source options for mining and corresponding costs range. From Brychcy et al. (2020).

Nevertheless, groundwater extraction is likely to suffer risks and disruptions in the future. A good example is the Los Bronces mine, which according to Brychcy et al. (2020), recently had to reduce output by 44 percent owing to a scarcity of water. This demonstrates that miners who rely on continental supplies of water will be at constant risk. According to the source, desalination and the usage of saltwater will increase by 230 percent in the next decade. It is important to note that most of copper porphyry mines are at high altitude which demands larger CAPEX and OPEX in case of utilizing seawater or desalination processes. This is mainly because moving seawater across large distances and to high elevations need noncorrosive piping in both pipeline and plant configurations, as well as greater energy in transportation due to increased viscosity and density.

Some possible considerations remarked by Brychcy et al. (2020) are the following:

1. **Legal:** potentially plans for a stronger regulatory framework will take place, in which large-scale mining projects will be required to utilize seawater.

2. **Social:** conflicts over the mining industry's exploitation of scarce freshwater sources damage community ties at existing operations and develop public opposition to new projects.

3. **Economic:** seawater is more costly than continental water and will remain so. Using unprocessed saltwater necessitates the investment and installation of specific pipes and facility modifications.

4. **Environmental:** the brine coming from desalination that is injected back into the ocean poses an environmental danger by disrupting local ecosystems.

### 4.2.2 Storms, heavy rain, and snow

Extreme events and heavy rain are likely to disrupt operations, deteriorate roads, and disrupt land transportation. Smith (2013) states that increasingly severe rainfall and extreme weather events have the potential to interrupt supply chains and transportation services for critical materials, manpower, energy fuels, and ore transfer to mineral processing comminution facilities and export terminals. All these consequences will ultimately limit production or reduce efficiency. Moreover, tailings dam collapse, landslides, drainage of polluted water into adjacent areas - and their associated remedial expenses, increases in environmental responsibility, consequences on community health and safety, and major potential for reputational damage are all risks associated with heavier precipitation according to Nelson and Schuchard (2011).

#### Cyclones and flooding

Heavy rains often cause operations to be disrupted, resulting in mine shutdowns, washed-out roads, and critically high water levels in tailing dams. Delevingne et al. (2020) mentions one open-pit mine in its database lost up to 10% of its annual production due to bad weather conditions. Moreover Scott et al. (2018) estimated the mining sector in Queensland to have lost AUS$ 2500 million as a result of the floods in 2010–11. Concerns have been expressed in regards to the extent to which increased floods might worsen pollution of habitats near mining sites. Acid Mine Drainage (AMD) is a process in which metal sulphides get oxidized when they come into contact with water, resulting in soil and water pollution, which has ramifications for the health of aquatic and terrestrial ecosystems, as well as humans.

Employee safety on-site and on the highways may be impacted by the increasing likelihood of more extreme precipitation and flooding. Some other risks involve flood waters staying in the mine pit, the more time they are there, the more time they have to absorb pollutants. Furthermore, when rivers recede, the discharge becomes more vulnerable as it represents a larger fraction of the river's volume (Smith, 2013).

Besides the above mentioned effects, increased rainfall may receive special measures to improve water treatment capacity due to flooding. According to Smith (2013), as flood risks rise, so will the threats to decommissioned sites, necessitating larger and more expensive flood protection. Additionally, Nelson and Schuchard (2011) mentions food security will be compromised by floods, natural catastrophes, and drought. Furthermore, flooding and increasing temperatures will hasten the development of tropical illnesses that have a negative impact on public health. Increased rainfall in some places might cause production to be disrupted, necessitating extra controls to improve water treatment capacity.

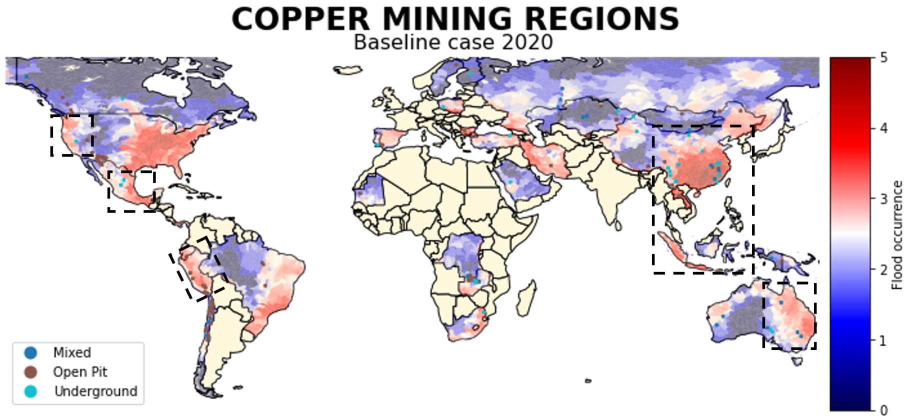


Figure 4.8: Global copper mining and flooding risk "wet zones": great portion of East Asia, Mexico, the Peruvian and Ecuatorian region, eastern Australia, and western North America. Own elaboration adjusted from Gassert et al. (2013)

Depending on the locality, flooding has a bigger influence on some commodities than some others (see Figure4.8). The problem is expected to expand, according to Delevingne et al. (2020), mainly in the six "wet zones" where extremely high rainfall is expected to increase by 50 to 60% this century: northern Australia, South America, and southern Africa in the summer, and central and western Africa, India and Southeast Asia, and Indonesia in the winter. Smith (2013) has raised concerns about proper preventive measures and proposes going beyond compliance responsibilities and investing in more deliberate flood control. The Ensham coal mine in central Queensland, for example, was inundated with more than 100,000 megalitres of water in 2008. Pumping it out and recovering a submerged dragline took four months. The entire expense was estimated to be around $300 million. However, it must be noted that floods are acute climate risks, as they normally involve larges amounts of water in a reduced time-frame. These by no means offset droughts (which are deemed as a chronic climate risk), both can happen in the same mining region independently.

**Landslides**

Pierre-Louis (2022) explains that landslides are caused by a variety of factors, including earthquakes, volcanic eruptions, and human action. However, rainfall is perhaps the most prevalent cause of landslides across the world. The soil's strength is substantially reduced as a result of this. When the strength of the soil deteriorates, it can hit a state where it collapses and just slides. Horton and Mancini (2008) explains this phenomena as land surfaces are kept together by a variety of forces, the most important of which is friction. A landslide occurs when something is added to interrupt this force on a slope. When gravity exceeds the force of friction, landslides occur. The friction between the bedrock and the overlaying silt is reduced by water, and the material slides downhill due to gravity. As a result, many landslides occur following rainstorms.

Heavy rain events are becoming increasingly common as a result of climate change. Because of the rain, landslide experts are alerting that climate change may increase the likelihood of landslides. Morevoer, High-magnitude storms and hurricanes, according to Scott et al. (2018), enhance the likelihood of waste rock sliding, tailings dam collapse, and more general earth movements in mining sites. However, Palmer (2020) notes that climate has a two-folded effect over landslides as heavy rain may cause more landslides, but droughts or more vegetation in some areas caused by climate change may make landslides less likely. In fact, Williams et al. (2021) found that mean annual rainfall and forest cover levels were both useful predictors of deep-seated landslide occurrence. However, their analyses showed that forest cover appears to decrease the likelihood of landslide occurrence, hence many landslides could have formed in response to native forest removal due to mining.

Many fatal landslides in mining have been reported. Howes (2020) mentions a landslide in Myanmar during 2020 which was sparked by torrential rains. This event killed at least 162 people in a Jade Mine. Pollon (2021) describes a nearly fatal event in Canada. Approximately five million tonnes of rock and ice crashed from the Canoe Glacier in British Columbia during the Pacific Northwest heat wave, barely eight kilometers from the Brucejack gold mine, where 600 people were working that day.

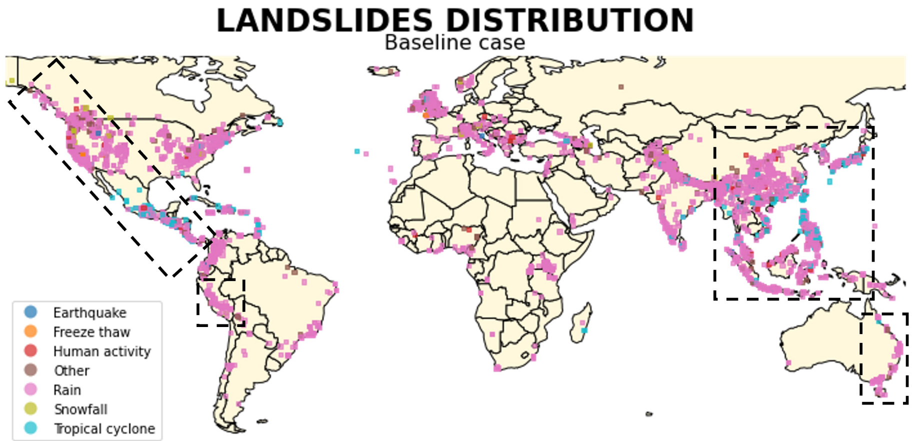


Figure 4.9: Global copper mining and flooding risk hot spots: East Asia, Mexico, the Peruvian and Ecuatorian region, and western North America. Own elaboration adjusted from Kirschbaum (2018)

Figure 4.9 displays landslides distribution across the globe where one of the main mining areas of concern is East Asia. Zhuang et al. (2022) explain that due to regular human activities (e.g. slope excavation) and mountainous topography for landslide occurrence, typhoon-induced landslides are the predominant major risk. These events have disastrous consequences for coastal communities and infrastructure. Usually they hit about the same time as typhoons, revealing complex failure processes caused by the combined action of wind, rain, and trees. In the typhoon-affected region, landslides accounts for the main catastrophic cascading impacts, resulting in huge mortality and economic losses in recent decades.

Merzdorf (2020) studied this phenomena and concluded that global warming will cause more intense rainfall, and this could lead to increased landslide activity. As Earth's climate warms, the water cycle is changing, including shifts in its annual monsoon patterns and rainfall. Heavy rain, like the kind that falls during the monsoon season in June through September, can trigger landslides on the steep terrain, creating disasters that range from destroying towns to cutting off drinking water and transportation networks.

### 4.2.3 Extreme temperatures

According to Smith (2013), more frequent days with temperatures exceeding 35°C combined with moisture, and water shortages raise the risk of heat-related diseases, which can impair decision-making and impact productivity as a result of more incidents, accidents, and fatalities. Rising temperatures are expected to rise the occurrence, prevalence, and geographical coverage of tropical illnesses like dengue fever, malaria, yellow fever, among others; posing health and productivity risks in the workplace. Nelson and Schuchard (2011) warns increasing energy demands to cool underground mines and surface facilities, however, underground cooling systems could be insufficient to handle temperature, water, and energy fluctuations. Moreover, the author also predicts hotter and drier conditions may increase wildfires that threaten facilities. Temperature variations that raise the energy demand and increase stress on transmission and distribution systems might cause supply disruptions. Restriction of energy might result in permanent reductions in output, lowering earnings and commodities prices.

#### Heat waves

NWS (2020) defines the heat index as the actual sensation of warmth to the human body when humidity and ambient temperature are coupled. This seems to have major implications for the wellbeing of the human body. When the person becomes overheated, they tend to perspire or sweat in order to cool themselves down through their evaporation. However, if the relative humidity of the atmosphere is high, the rate of evaporation from the body drops provoking it to overheat, or in other words, a heat stroke (see Figure D.1 in Appendix).

Extreme heat will reduce employee productivity and raise cooling costs in hotter locations including Australia, China, and areas of North and West Africa. Furthermore, it has the possibility to jeopardize personnel's health - and, in severe cases, their lives (Delevingne et al., 2020). Likewise, Dasgupta et al. (2021) notes that both labour supply and productivity are projected to decrease under future climate change in most parts of the world, and particularly in tropical regions. Parts of sub-Saharan Africa, south Asia, and southeast Asia are at the highest risk under future warming scenarios. The author explains this is due to a decrease in performance during working hours - labour productivity - e.g. when workers under severe heat stress slow down and take more breaks to re-hydrate and cool down. Additionally, excessive body temperature and dehydration can increase the number of mistakes made, resulting in increased accidental injuries. Summarizing, key drivers that have an direct impact on mining labour costs are productivity and wages.

Scott et al. (2018) noted that higher temperatures at Australian mining sites may challenge mines ability to source people, provide health and safety for work-

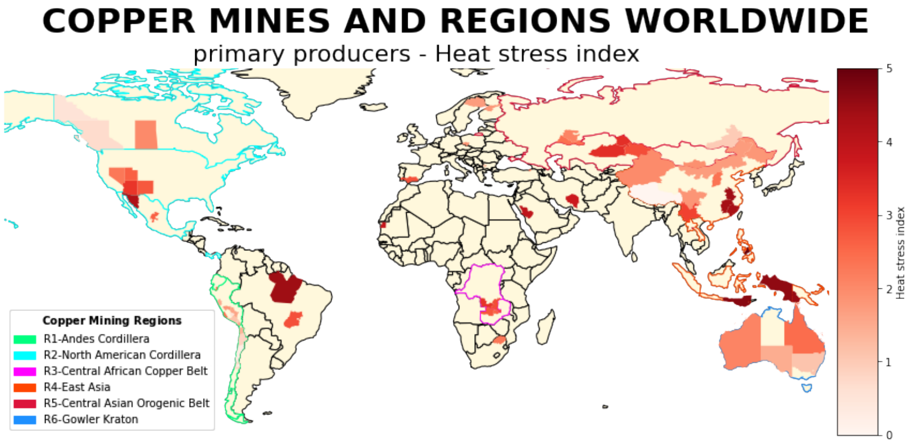


Figure 4.10: Heatwaves hot spots. Adjusted from Finneran (2010).

ers inside the mine site, maintain production at expected rates, and preserve the industry's competitiveness in the long run. The author remarks that the production stage is expected to be the most vulnerable to future climatic events and climate change. Moreover, water and energy access were identified as risks, including the potential of power outages due to large-scale disasters.

**Wildfires**

Climate change exacerbates wildfires by increasing dryness, high air temperatures, low humidity, lightning, and strong winds, leading to hotter, drier, and longer wildfire seasons. Simultaneously, wildfires exacerbate climate change by destroying fragile and carbon-rich ecosystems such as peatlands and rainforests. This transforms landscapes into tinderboxes, making it more difficult to slow global warming (WMO, 2022).

Wildfires also constitute a considerable climate risks for some mining regions. According to Smith (2013), bushfires pose a threat to human life as well as mining infrastructure and assets, as a result, most mining businesses have wildfire prevention strategies in place. Although fires pose a risk to coal mines, mines producing other amenities have also been affected by this phenomenon. A good example is mentioned by Skidmore (2021) when Teck Resources resumed its operations at the Highland Valley copper mine in British Columbia after shutting it down due to the threat of wildfire activity in the area during August 2021. Another example is provided by Kosich (2010), when Capstone's Minto Mine in Yukon evacuated a big portion of its operators from the mine due to wildfires, compromising its target output. Figure 4.11 displays the wildfires hotspots in the copper mining regions.

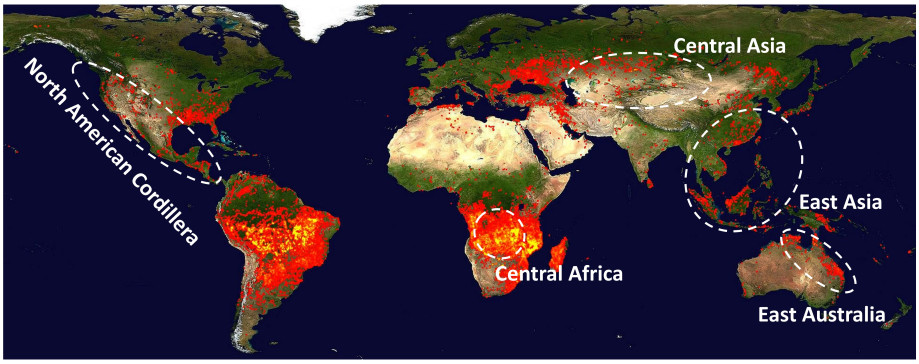


Figure 4.11: NASA's Terra satellite shows fires around the world, white dashed lines highlight copper mining region hot-spots. Adjusted from Finneran (2010).

WMO (2022) reports that record-breaking wildfire outbreaks have occurred in recent years all throughout the world, from Australia to the Arctic to North and South America. If greenhouse gas emissions continue at their current rate, tropical forest areas in Indonesia and the southern Amazon are also expected to witness significant wildfires.

### Permafrost thawing  glacier melting

Permafrost is ground that has remained permanently frozen for at least 2 years. In mountainous areas, permafrost zones typically exist above a certain altitude. Permafrost zones' rocks are glued together by ice fillings in their cracks and crevices. As the air temperature increases each year, Palmer (2020) believes that the warming, and even thawing, permafrost is weakening rock faces and leading to rockfalls. The theory is difficult to prove as it is not something visible like a glaciers. When the scientists analyzed their inventory of rockfalls, they found that all of the rockfalls stemmed from areas in permafrost zones and that rockfalls were more likely in regions of temperate permafrost (close to 0°C). They also found that the frequency of rockfalls increased during the hottest summers.

Therefore the integrity and safety of arctic and high-altitude infrastructure is jeopardized by the warming and thawing of glacier permafrost, putting sustainable development at risk. Temperature increases, active layer thickening, and thaw-related hazards such as thermokarst and mass wasting are all risks to infrastructure posed by permafrost change. Rising human activity worsens these effects, which are generally connected to global warming. Moreover, Hjort et al. (2022) studied damage to infrastructure and determined that it can be significant, with up to 80% of structures in certain Russian cities indicating destruction and up to 30% of road surfaces on the Qinghai–Tibet Plateau claiming damage. Infrastructure damage is expected to increase as a result of global warming, with 30–50 percent of essential circumpolar infrastructure expected to be at high risk by 2050. As a result, infrastructure expenses associated with permafrost degradation may reach tens of billions of dollars by the second part of the century.

Furthermore, Scott et al. (2018) warns that higher temperatures could increase the rate of glacial melt along Chile's Andean chain, which could have substantial impacts on water availability given the country's dependence upon runoff. Glacial melt leads initially to an increase in run-off and associated water availability, followed by a long-term decline.

However, permafrost thawing could open up to new opportunities. Nelson and Schuchard (2011) stated that warmer temperatures will open new mineral-rich areas for exploration and will reduce heating costs. Warming temperatures in the Arctic and other cold climates will make it easier to operate and reduce heating costs. Permafrost thaw on winter ice roads will interfere with consistent and timely supply of critical materials, potentially halting production at sites in the Arctic. The time available for haulage on ice roads will be shorter. Warmer arctic and subarctic temperatures will open areas not previously accessible for exploration that are likely to contain a vast store of mineral wealth.

### Rising sea level

Rising sea level might be one of the least studied physical effects on mining as it may not have a straightforward effect. However, Smith (2013) notes sea level rise and more intense extreme weather events may negatively affect port availability as well as interrupting and delaying operations. Costs for transport may rise in such circumstances. Moreover, Nelson and Schuchard (2011) warns this phenomena may force migration of coastal civilizations, whose movement to new areas may exacerbate social problems and conflicts in host communities. Sea-level rising and frequent storms may affect port availability, interfering with timely transport to market. Demand for rail and road networks as alternative transportation mediums will rise, increasing costs. Rising sea levels may require construction of sea walls or other retaining structures, stimulating the cement industry

### 4.2.4 Other physical risks

**Labour migration due to food security and climate**

It was discussed in the previous chapter how persistence in talent shortage in the mining industry as a major factor for lately labour costs increase and a factor that poses greater pressure on existing staff to do more with less, reducing employee productivity. However, shortage might be also boosted by the migration of current professionals working at some climate vulnerable locations over time. Moreover, Ozcan and Strauss (2018) suggests the impacts of climate change may cause hundreds of people to flee their cities. Those impacted may be forced to relocate to other cities or countries in search of better living circumstances and resources. According to Maslin (2020), catastrophic climate change would need 3.5 billion people to relocate if they wished keep living under the same temperature range as it is now. Even if aggressive climate regulations limited global warming to 2 degrees Celsius, they conclude that 1.5 billion people would still have to relocate. In this context, Smith (2013) warns drought, extreme weather, and flooding will undermine food security, exacerbate poverty, trigger migration, exacerbate social unrest, and intensify conflict over natural resources.

The research done by Loboguerrero et al. (2019) reveals that by 2050 the world will encounter an unprecedented difficulty of food security by 60% to feed a predicted global population of 9 billion people. Such a challenging purpose is complicated by increasing limits on land and water availability for agricultural, pasture, and animal production, as well as the existing and future detrimental effects of climate change. Moreover, the author alerts that due to progressive climate change, farming is projected to become unfeasible in many regions, particularly in coastal towns where sea-level rise will progressively cause severe effects such as submergence, coastal flooding, and erosion.

McMichael (2013) notes climate change will adversely affect food security in many regions and this may contribute to migration where, for example, people move to areas where agricultural livelihoods and food sources are more secure. Moreover, climate change is projected to cause increases in human population movement in coming decades, and the nature of some anticipated migration pathways may lead to food insecurity in sites of settlement and relocation.

Figure D.3 in Appendix shows food development under the most severe scenario in terms of climate physical risks. In these scenarios it can be observed an overall increase of crops yields around the globe, probably following the population growth rate. However, most of the regions will face food security problems with maize as their yield is forecasted to be lower than the baseline. Moreover, the Central African region is expected to face problems with wheat yields as well. However, as mentioned before, given that the population is expected to grow, so do the crop yields overall. This means, that figure D.3 do not allow to analyze if there will be actually food security problems. Nevertheless, Loboguerrero et al. (2019) studied these gaps with the severity of impacts of climate change on maize, wheat, and rice.

Figure D.4 illustrates the results of this study allowing to see the difference between countries, in this case countries with a large cereal gap and high impacts of climate change are most vulnerable (coloured in red). Moreover, results displayed in Figure D.4 in Appendix shows a low overall risk of food security in the copper mining regions studied for this work. However, among all the copper region particularly Zambia and DRC in Africa, and in a minor - scale the Australian region as well - there are moderate-high risks of food security in the future.

Warner et al. (2010) studied climate change induced migration. The study predicts that by 2050 faced with an unprecedented scale of environmental change, migration may be an adjustment mechanism of first resort or a survival mechanism of last resort. Considering the different skill levels, highly skilled migrants generally move to improve income and quality of work, whilst low-skilled migration is typically driven by the expectation to reduce economic insecurity. The author noted in particular that pressure is increasing on dry land ecosystems for providing services such as food, and water for humans, livestock, irrigation, and sanitation. Climate change is likely to increase water scarcity in regions that are already under water stress as they accommodate close to a third of world population but harbor only 8% of global renewable freshwater resources. Figure 4.12 displays migration risks hotspots on the Central African Copper belt and East Asian copper mining regions.

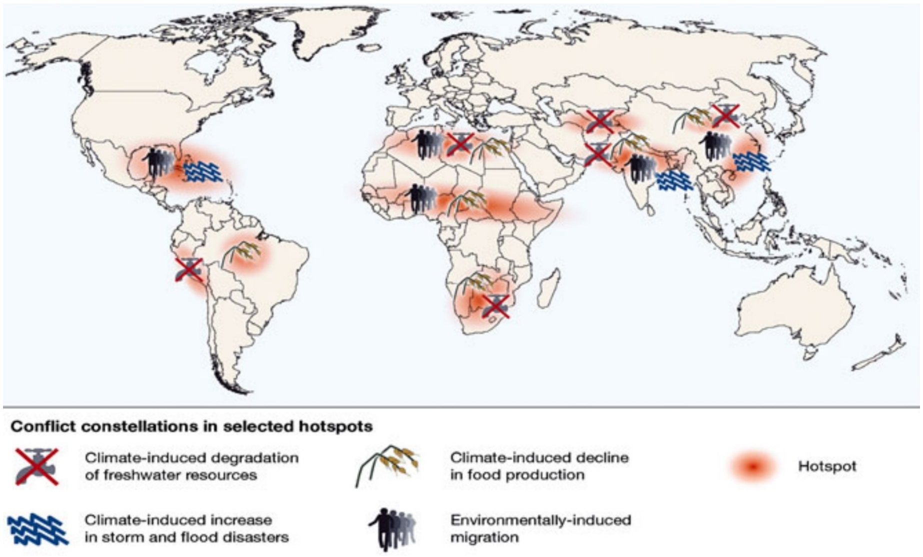


Figure 4.12: Environmental hotspots and migration. From Warner et al. (2010)

Based on both figures 4.12 and D.4, it can be concluded in this section that climate-induced decrease of food security and environmental migration poses a risk for East Asian, Zambia and DRC mining regions for this study.

### Conflicting indigenous and local communities

Climate-related organizational and operational risks for mining activities are not only significant in and of themselves, but the accompanying reputation risks to the organization and its social licence to operate may be potentially permanent in nature. Some good example of how climate change-induced poor management of mining impacts are provided by Assan and Rosendelf (2012), these may cause conflict with indigenous and local community and include: tailings dam collapse due to severe flooding or rising sea levels; competition (and, in some cases, potentially conflict) with host citizens and local industries over access to limited reservoirs of water during and/or following a drought; heat and dust-related health stress among local residents; and meeting community expectations.

Indigenous communities, some who live a precarious economic and social existence, are particularly vulnerable to climate change and mining activities. For instance, impacts of the former are already being experienced in Australia through dramatic weather events such as floods, bushfires, impacts in their local ecologies and higher risks due to crop failure closeby. Other, more gradual changes, such as rising sea levels in the north of Australia, will have long-term negative consequences on communities, including the possibility of forced relocation. On the other hand, mining is a permanent threat as leads to potential disruptions that may include restricted access to traditional land and sacred sites, the destruction of the sites themselves, and threats to traditional food supplies, which will in-turn deplete health regimes.

Ecuador Copper Mine Mirador is a good example of the above. They have been located in an environmentally and culturally sensitive territory that encompasses Indigenous Shuar community land in the Ecuadorian Amazon. The Chinese consortium, which has been unable to advance with its project due to intense demonstrations and resistance, has taken adaptable actions with local communities in order to stabilize its mining investment (Rodriguez, 2021).

### 4.2.5 Case studies

To assess physical risks into case studies, six primary copper mining regions were conveniently defined based on copper metallogenic belts, their geology and due to their similitudes in topography and climate conditions as it follows:

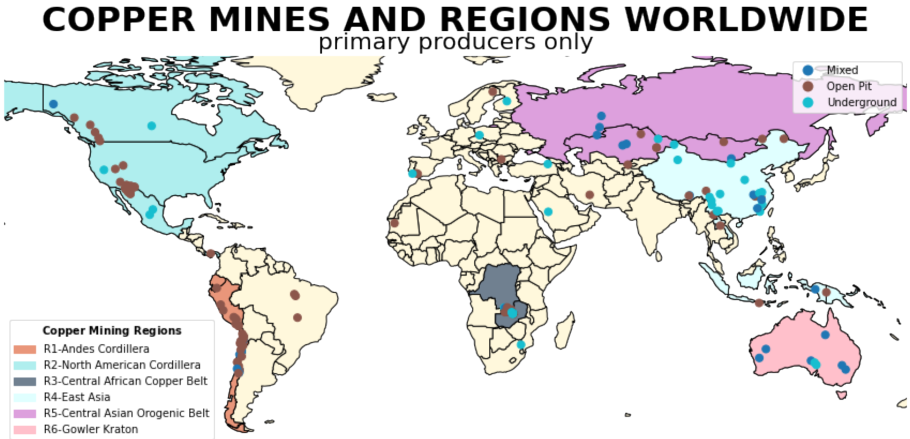


Figure 4.13: Copper mines worldwide by type of mine. Own elaboration adjusted from CRU database.

This section links previously specified climatic indices to case studies. This aims to quantify the impact of these metrics on the mining operation, and therefore to provide a reference for what it would mean if these indices were high or low. These indices were used to determine the risk of each specific mine based on the current data, whilst analyzing case studies of each of the copper mining regions previously defined, in order to correlate these indexes with historical business disruption.

This approach was adopted since during the review of the case studies it was revealed that there is little historical information linking disruption of operations to physical climatic risks. Therefore, by quantifying each of these risks, in the form of indices, and correlating them with disruption of operations, it is possible to extrapolate to all mines for which there is no information on how the physical risks have affected their operation. In other words, this exercise allows one to answer the questions, "What does a water stress index of 4.2 mean for Mina Justa-Marcona?", "What does it imply if this index goes up or down?". The case studies are described in detail in the study's appendix.

On the other hand, this methodology is far from being optimal nor scientific, but given the scarcity of data, it provides a measurable reference of the climatic effects on mining operations, which is crucial to be able to build the model later.

### 4.2.6 Acute operations' consequences assessment

#### Financial losses due to business disruption caused by climate risks

After going through all the case studies, the data was analyzed to find relations between the previously defined climate physical risks indexes to their disruption to mines operations. Due to the lack of data, all physical risks were analyzed together to provide sufficient points and thus increase the reliability for this correlation displayed at Figure 4.14:

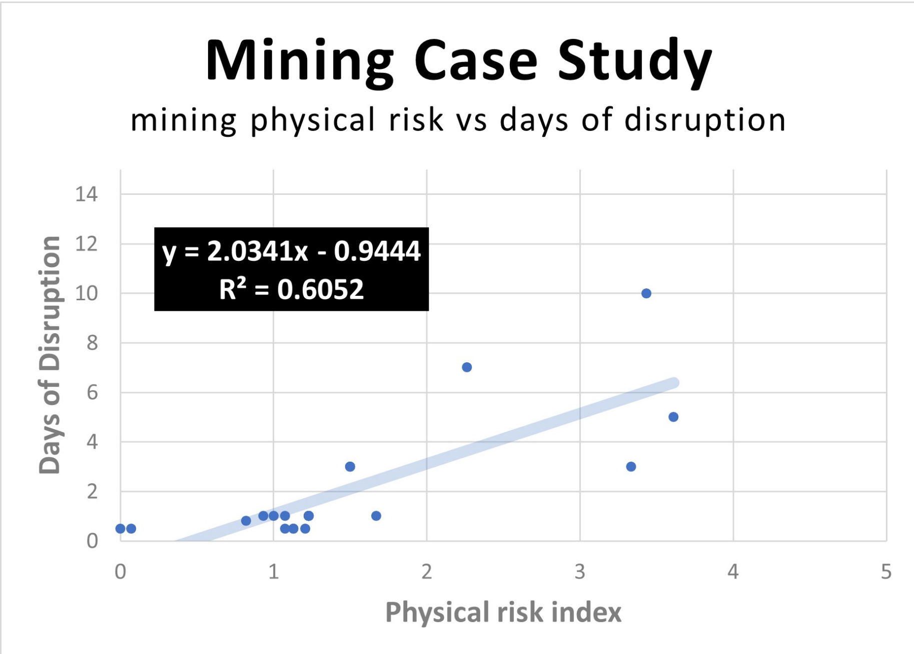


Figure 4.14: Overview of physical risks in Central Asian Orogenic Belt mining region. Own elaboration.

The correlation coefficient obtained is 0.6 which for the purpose of this study is acceptable given the lack of points, as the main purpose is to provide some reference of the potential financial impacts to be applied over all the mines based on their physical risks.

This correlation will then be used in the model to assess physical risks adjusted over all climate scenarios for all the mines in this study.

Interviews were held with insurance and reinsurance companies to define the approach to quantify the climate risks premiums. The recommended approach was to consider the amount of days of disruption and the loss of production as a proportion to the yearly output. An overview of the distribution of these indices across the globe can be seen in Figure D.2 in the Apendix.

### 4.2.7 Chronic operations' consequences assessment

**Water index - desalation**

In the same way, it was possible to find the copper mines that are now utilizing desalination by using the case studies and research. Thus, the analysis in the model will use the average water stress of those mines that use this process as a reference and extrapolate it to the rest, assuming that by 2030, the mines that exceed this limit will have to operate seawater desalination in order to continue operating, failing which there will be unsustainable problems with the surrounding communities or they will simply be unable to operate due to a lack of available water.

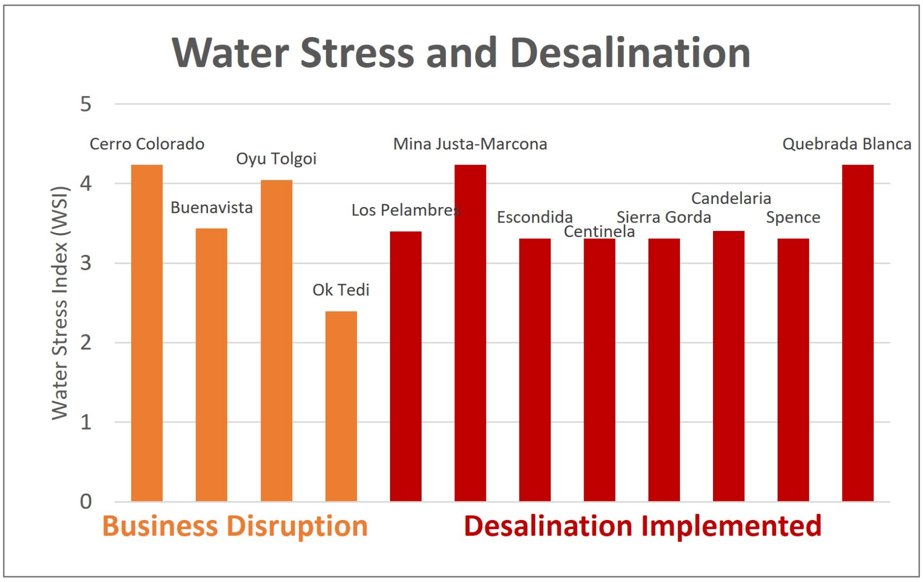


Figure 4.15: Overview of water stressed regions and desalination. Own elaboration based on studied cases and (BNAmericas, 2022).

Figure 4.15 summarizes the analysis performed. The limit that will be used in the model is a water stress of 3.56. Thus, the model will include an average desalination cost for all mines that exceed this defined limit under different climatic scenarios. It is important to mention that only operational costs and not investment costs are considered for this analysis.

**Other potential effects to consider**

While no specific cases relating labour and food security in the mining industry were found, this must be taken into consideration as it is closely related to water stress as well. Thus, for instance, in the case of the Buenaventura mine, if the water issue worsens as a result of industrial activity and climate change. This will cause local communities to react and ultimately generate their migration, as will the company's employees who were previously willing to live there. And as mentioned earlier, this will potentially lead to a job crisis in remote industries, such as mines.

## 4.3 Transition risks

Many discussions concerning climate-related risk have previously focused on the immediate and physical consequences of climate change, which is mostly caused by human activity. Transition risks, however, are intended to influence the latter by imposing new regulations such as fiscal policy (e.g., carbon pricing; public investment or subsidies), structural policy (competition or labour market policy to help smooth the transition, influencing wage and price dynamics), and regulation and standards are examples of such policies (e.g. setting emissions standards or targets for certain sectors). These transitions may suggest that certain economic sectors are facing significant shifts in asset prices or higher operational expenditures. Moreover, companies will be under the pressure from investors, lenders, and insurers to reduce carbon obligations, create adaption strategies, and include climate change risk in due diligence. Share price and capital availability will be impacted by how climate consequences are managed.

New applications, particularly those connected to energy efficiency, as well as cutting-edge technology like fuel cells, carbon reduction, diesel emission control, and water purification may result in an increase in demand for other commodities. New revenue streams will be created by patenting and marketing extremely energy-efficient mining and processing technology. Due to all this, it is relevant to compare transition risk to climate risk in terms of jeopardizing financial stability across the economy as organizations are compelled to act.

Transition risks have macroeconomic consequences because of a fundamental shift in energy and land usage that will influence every sector of the economy. At a high level, this might result in part of the current capital assets becoming "frozen," as well as labour market frictions as the economy changes to reduced, and eventually net-zero, emissions activities. The magnitude of the effects will be determined by how gradually and reliably this transition occurs, as opposed to how suddenly and disorderly it occurs, and how investment in new technology affects productivity.

Some of the main transition risks can be classified into (1) Policy and Legal Risk, (2) Technology Risk, (3) Market Risk, and (4) Reputation Risk. Nevertheless, for the purpose of this study we will just focus into the financial effects in the cost curve under different climate scenarios driven by (1) in form of carbon price induced to mining as well as (2) labour productivity due to new regulations; and (3) as increased cost in energy overall. This simplification is due to the available quantitative data to be assessed for this model.

### 4.3.1 Greenhouse Gases

**Carbon dioxide emissions in mining**

Figure 4.16 allows us to visualize the hot spots of the most carbon intensive copper mines around the world. At first glance, there is no local phenomenon, but rather it is unique to each mine.

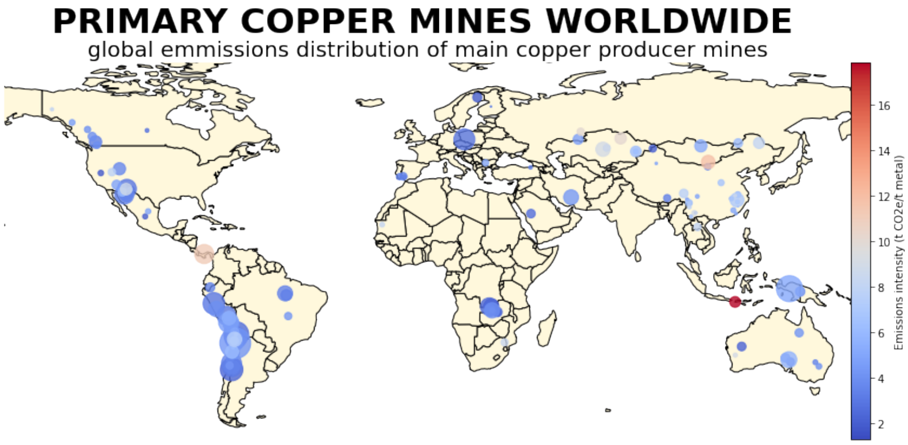


Figure 4.16: Global copper main producers carbon dioxide intensity versus output map in 2021. Own elaboration adjusted from CRU database.

On the other hand, Figure 4.17 allows us to visualize the supply of copper at a global level with respect to $CO_2$ emissions, this illustration shows that close to the 75% percentile there is a constant slope with respect to emissions, however, this slope then accelerates noticeably until the end of the accumulated supply.

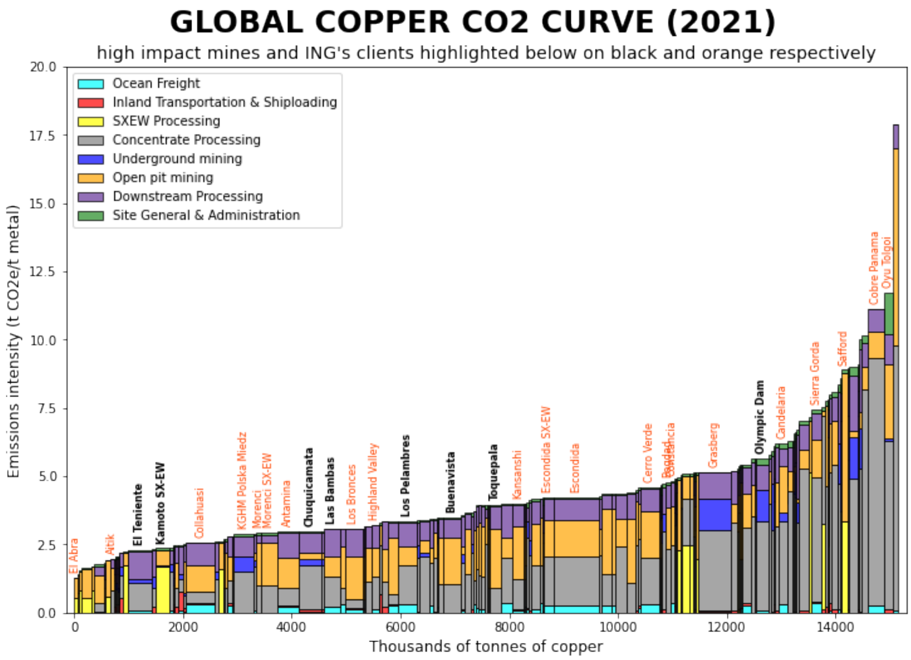


Figure 4.17: Global copper main producers carbon dioxide intensity versus supply curve. Own elaboration adjusted from CRU database.

The classification also shows that a large part of the emissions come from the processing of copper concentrates, which includes the crushing, grinding and flotation process. This is followed by mining activity, which includes drilling, blasting, loading, and hauling the ore to the processing plant. Moreover, Smith (2013) mentions that most energy is used for comminution, materials movement, mineral ore separation/froth flotation and ventilation of underground mines. Smaller overall amounts of energy are used for blasting, drilling, dewatering and operating mine site buildings and staff accommodation. The share of emissions is consistent with the energy consumption we have reviewed in the previous chapter.

### Carbon prices

Energy efficiency measures are the least expensive way to reduce greenhouse gas emissions. Furthermore, mining firms can decrease their vulnerability to the carbon price by identifying and methodically lowering the major sources of greenhouse gas emissions. While each mine is unique, the majority of greenhouse gas emissions are typically attributed to the sources mentioned before.

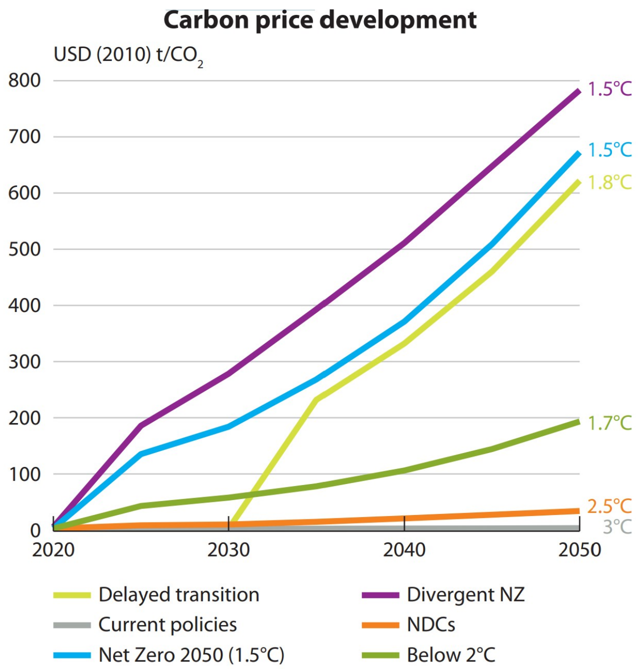


Figure 4.18: Carbon price by scenario till year 2050. From Elderson and Breeden (2020)

Figure 4.18 shows the different carbon prices for each of the scenarios. As described above, a disorderly transition scenario would result in aggressive changes in the carbon price. This, in turn, would be financially devastating for companies that have not been able to make a prompt transition.

### 4.3.2 Cost of energy

Increased demand and rising prices - due to limited natural gas supplies, carbon taxes, and expensive alternative energy sources, will increase costs (Nelson and Schuchard, 2011). On the supply side, Smith (2013) notes green energy would be generated considerably more effectively in the orderly transition scenario, allowing energy prices to rapidly fall. As a result, under the baseline scenario, energy prices would finally decrease below those associated with the hot house world scenario. In contrast, a delayed and abrupt adoption of green technology would result in estimated energy prices being relatively higher across the majority of the projection horizon under the disorderly transition case.

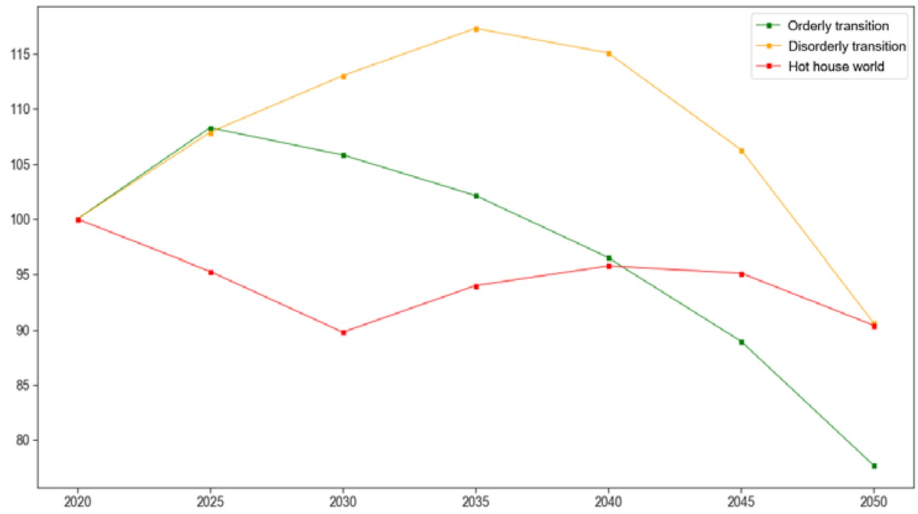


Figure 4.19: Projected energy price paths till 2050. From Elderson and Breeden (2020)

Green technologies used in a timely and efficient manner would not only put strain on energy prices through lower energy production costs, but also by reduced energy consumption. Figure 4.19 precisely suggests that strong consumption would ascend above the levels referring to the reference scenario over the a whole forecast under the hot house world scenario. Furthermore, the disorderly transition scenario's delayed and abrupt incorporation of green technology into the industrial process results in a strong and fast drop in energy prices around 2030.

# Chapter 5

# Model

**Introduction**

In this section, all the previous background will be summarized into a comprehensive quantitative model. Firstly, in Chapter 3 we reviewed copper mining by locating where and how most of the assets are located - with their corresponding risks; what is the nature of this commodity and main drivers for its demand and supply. Moreover, Chapter 4 allowed the reader to understand how these projects are financed as well as understanding the operational costs that lead to the whole copper supply cost curve. Operational costs were also broken down to understand their form and rationale. Both the mining type and a general country perspective were analyzed to gain a better understanding. Finally, in chapter 5 the baseline for the physical risks in form of different indexes for each of the assets have been defined. Moreover, the research done with the case studies allowed to establish thresholds which will be used in the model. Likewise well as the climate scenarios to be applied to stress test primary copper producers.

In this chapter, however, both physical and transition climate risks are assessed for each individual copper mine. This will be done in two different forms:

1. the first one is meant for physical risks and takes the previously defined baseline for a specific year (2020) and adjust it to the different climate scenarios through the existing input data for each of them. In other words, a mine with a certain water stress will be corrected mathematically according to variables such as precipitation level, air temperature, etc. , for a particular scenario. Then the financial effect of this corrected index will be added to the total cost of production to compare all mines.

2. the second method is for transition risks and mainly applies corrections based on changes in key variables over existing costs for 2030 and 2050. A good example would be energy costs, where its variation would be with respect to the base scenario would be known, then correction to the whole item is then applied.

The reader should expect from this model a reference to how mines would behave financially under certain possible future climate scenarios. It is a reference since it assumes that mines would not change their way of operating independently of the setting, with the exception of desalination of water. It also ignores the financial impact of many other important factors, such as future technological changes such as automation, new energy sources, new materials, methods of extraction, among others. Having said that, this model does not include such factors, so these scenarios should not be considered realistic, but rather to analyse the level of exposure that these mines would have if they continued to operate just like they do today. **Given these assumptions, this model is regarded as static**. Knowing this information shows the level of effort-change-investment that each of the mines would have to generate in this timeframe to avoid potential financial consequences. Moreover, it highlights risks and identifies priorities to improve.

## 5.1 Assumptions, uncertainties, and limitations

This section will detail all the assumptions, uncertainties, and limitations involved in this model:

1. Supply remains constant regardless of the climate scenario. Also, future copper projects from new deposits that may be found are being ignored.

2. As mentioned above, it is assumed that mines do not make decisions based on climatic scenarios except for desalination of seawater if water stress exceeds the pre-established limit. This for example means the model in 2050 assumes no action from mining i.e. no investment in renewable energy and just keeps their operations as it is.

3. It is also assumed that these normalized indexes from 0 to 5 are comparable in terms of their impact to the number of disruption days of the operation. This is clearly an oversimplification, however, as mentioned above, this simplification's objective is to give a reference or guide to what the monetary impact would be on these mines. The study of this particular factor would require much more sophisticated methods than those applied in this thesis if a more realistic value is desired.

4. Normalization or indexing might not be comparable. Frequency of these events is disregarded and index consider provinces which vary in size, which mean in some provinces the analysis may be unnaccurate.

5. The model makes no distinction between whether a mine operates underground or open pit.

6. The model corrects the indices using variations provided by the NGFS climate parameters. This is done in a linear way assuming that there are no parameters that weigh more than others in the correction of this index.

7. The model ignores the frequency of weather events causing disruption, but assumes an annual disruption correlated to the magnitude of each index. In other words, if a mine has landslide index of 0 its impact in a yearly basis will be unrelevant, however if this index is high, it is expected their proportional in the days of disruptions yet to occur

8. Water desalination is assumed after the average threshold is surpassed. this assumption ignores localities tolerance or how strong the influence of local communities/politicians are to enforce a law to make companies

desalinize water. This is a big investment that has certainly a influence on the overall costs, thus companies will be reluctant to do it by their own initiative in most of cases. In the best case, this threshold should be based locally and take other factors into consideration (social, community density, agriculture nearby, etc)

9. Water desalination is disregarding the fact of mines being in landlocked lands, or mines that are at great heights. This is also inaccurate

10. The model ignores the vulnerability of each specific asset, which is its response to climate risks. In other words, two mines in the same location will be rated with the same physical risks regardless if one of them is better prepared to mitigate those risks.

11. This model is also limited to the source's data assumptions and errors.

12. Labor productivity being a driver for increased labor costs assumes all the manpower will keep doing the same tasks. This does not acknowledge the fact that technologies may decrease actually the amount of labor required as robotized-automated equipments substitute current jobs. Unfortunately there is no reference on this, for which this is an improvement to be recommmended.

## 5.2 Construction

This work has compiled great amounts of data from various sources in order to link them and thus analyse what would occur to copper mine costs in a specific climate scenario. The limitations, uncertainties, and assumptions of this simplified model were previously addressed and clarified. In addition, the variables that have been used to characterize the baseline have also been defined, as well as those that are used to adjust the baseline to each of the scenarios. Figure 5.1 describes the logic of the model with respect to the relationship of variables and the cost curve.

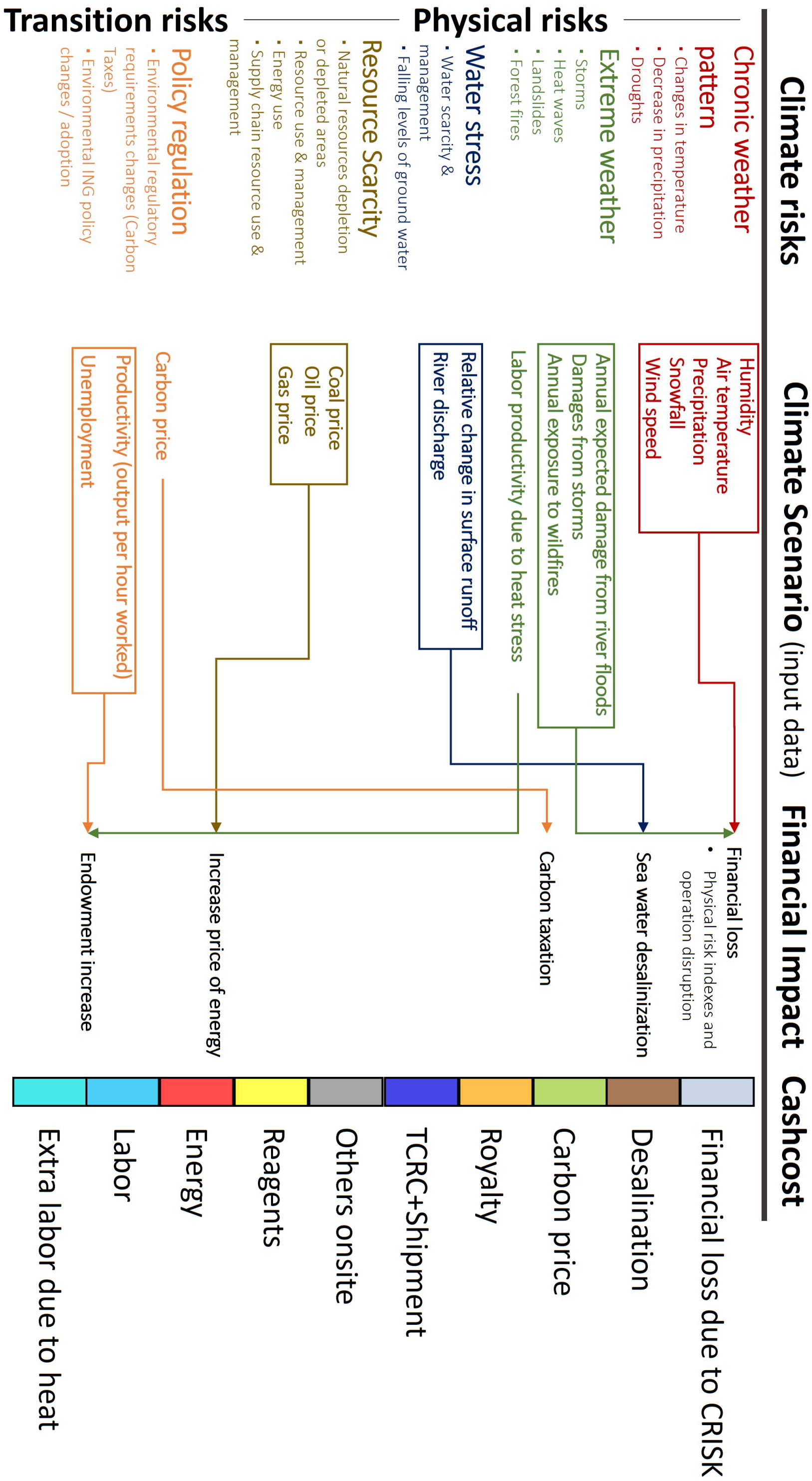


Figure 5.1: Model approach rationale. Own elaboration.

The following subsection will explain the methodology applied in the model

### 5.2.1 Productivity and loss of productivity due to heat stress

The labour costs of the mine are adjusted for productivity in each scenario, for each particular year and geographic region where the particular mine is located, as shown by the following equation:

$$Labor_{adjusted_{i,k,j}} = \frac{Labor_{baseline_{i,k,j}}}{100\% + \%\Delta productivity_{i,k,j} + \%\Delta heat\,productivity_{i,k,j}} \tag{5.1}$$

### 5.2.2 Energy costs correction

In the same way, energy costs for each mine are adjusted based on energy price fluctuations. These costs take into account the type of energy that would be available in each scenario, i. e. the proportion of fossil and renewable energy sources.

$$Energy_{adjusted_{i,k,j}} = \frac{Energy_{baseline_{i,k,j}}}{100\% + \%\Delta Price_{i,k,j}}$$

(5.2)

### 5.2.3 Carbon prices

The costs associated with the carbon price is the simple multiplication of the carbon price in each scenario, region, and year with the respective emissions of each mine for each year under study.

$$CarbonTaxes_{i,k,j} = Emmisions_{i,k,j} \cdot CarbonPrice_{i,k,j} \tag{5.3}$$

### 5.2.4 Financial losses due to climate physical risks

Financial losses associated with physical climatic risks consider potential disruption days, which are estimated based on the correlation with physical risk indices and disruption days presented in the previous chapter. Thus disruption days are estimated as it follows:

$$Ddays_{mine_i,scenario_k,year_j} = 2.0341 \cdot Pindex_{mine_i,scenario_k,year_j} - 0.9444 \tag{5.4}$$

Where:

$$Pindex_{mine_i,scenario_k,year_j} = \sum^{i,j,k,l} Index_{i,j,k,l} \tag{5.5}$$

In this case, it is assumed that for each day of eruption the mine must at least assume the fixed operating costs; in this case, by way of simplification, all costs are assumed. So if a mine has 10 days of disruption, it is assumed that the costs of the mine increase proportionately by 365/355.

$$FLoss = Cashcost \cdot \frac{365}{365 - Ddays} \tag{5.6}$$

**Heat stress index**

The adjustment of the heat stress index takes into account the two main variables that define heat stress, which are temperature and humidity. In addition, the evolution of heat waves is included as a corrective factor. To adjust the heat stress index, the variation of all these parameters relative to the baseline in each of the scenarios and years is considered.

$$HSI_{adjusted} = HSI_{base} \cdot (100 + \%\Delta_{Temperature} + \%\Delta_{Humidity} + \%\Delta_{Heatwave}) \tag{5.7}$$

**Flood index**

In the same way, to adjust the flood index the variation of precipitation as well as the surface runoff were considered.

$$Flood^{index}_{adjusted} = Flood^{index}_{base} \cdot (100 + \%\Delta_{Precipitation} + \%\Delta_{Surfacerunoff}) \tag{5.8}$$

**Landslide index**

Since the main factors that make landslides more frequent - as we studied before, are the presence of water on the land, both rainfall and surface flow are considered for the purpose of adjusting this index.

$$LSI_{adjusted} = LSI_{base} \cdot (100 + \%\Delta_{Precipitation} + \%\Delta_{Surfacerunoff}) \tag{5.9}$$

**Wildfire index**

In regards to wildfires, this index was adjusted based on the variation of the humidity, wind, and the expected evolution of areas affected by wildfires.

$$WFI_{adjusted} = WFI_{base} \cdot (100 + \%\Delta_{Wildfire-area} - \%\Delta_{Humidity} + \%\Delta_{Wind}) \tag{5.10}$$

**Water stress index**

Finally, the adjustment of the water stress for each scenario takes into account the variation of the rainfall, the discharge of the rivers and the temperature.

$$WSI_{adjusted} = WSI_{base} \cdot (100 - \%\Delta_{Precipitation} - \%\Delta_{Rdischarge} + \%\Delta_{Temperature}) \tag{5.11}$$

### 5.2.5 Desalination

Desalination costs will be assumed whenever water stress indexes in the region where a mine operates surpasses the threshold established in the previous chapter based on cases studies (3.6). These costs refer to Brychcy et al. (2020) as shown in the figure 5.2. To simplify the model and simulate in the acidic case, the cost of this operation for high altitudes is considered, 483 USD per tonne of copper.

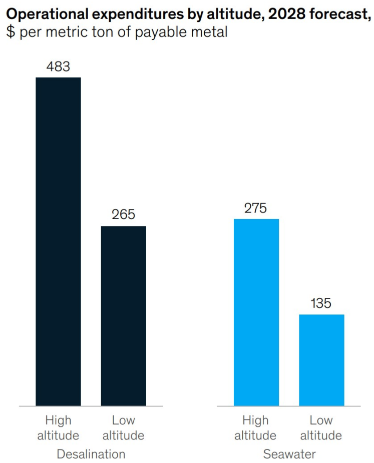


Figure 5.2: Water-source options for mining and corresponding range of costs. From Brychcy et al. (2020).

## 5.3 Results

### 5.3.1 Mines cost curves

**Current policies - Year 2030**

As mentioned above, the scenario of current policies is the scenario with the highest physical risks of the three chosen ones. However, it can be observed that for the short term there are not great differences between the climate scenarios, as these changes will be subtle and therefore the divergence will be smaller.

In this specific scenario it can be observed that the cost curve places the 50% percentile around 150 cents per pound of copper, and 95% in the 250 cents per pound. Water-stressed mines such as Collahuasi, El Teniente, Cerro Verde, among others, are expected to have to resort to desalination at this point, so their costs will increase considerably. As a result, mines that were previously on the most cost-competitive side (left) now due to desalination and, to a lesser extent, disruption of operations due to physical hazards – are now on the right.

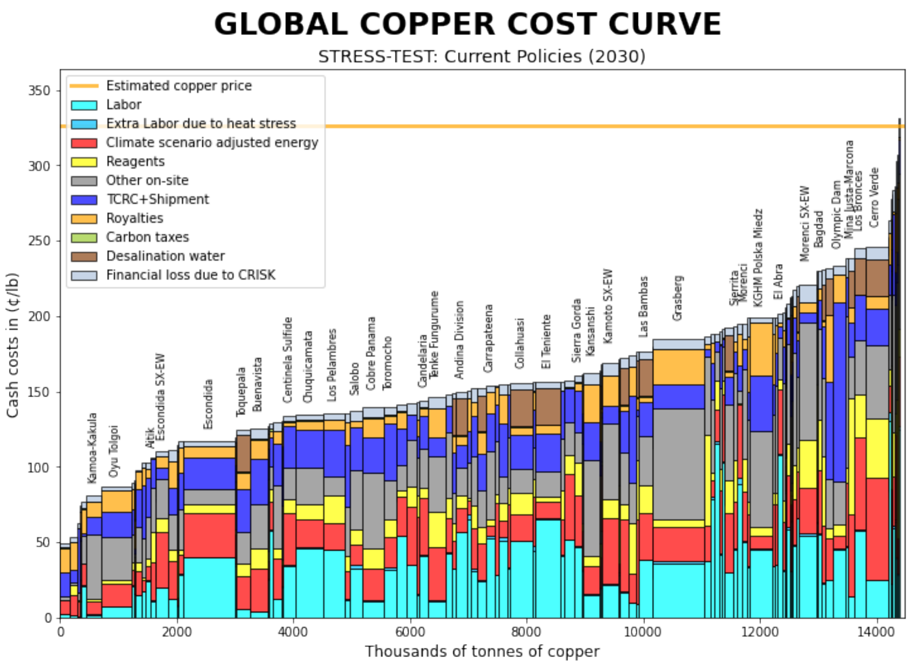


Figure 5.3: Global cost curve for primary copper producers - current policies scenario in year 2030. Own elaboration.

### Delayed transition - Year 2030

This scenario is very similar to the previous one, because the physical risks of both are identical, and the two have not implemented significant carbon prices, however, the carbon prices of delayed transition are slightly higher than current policies, which is the reason why the cost curves differ.

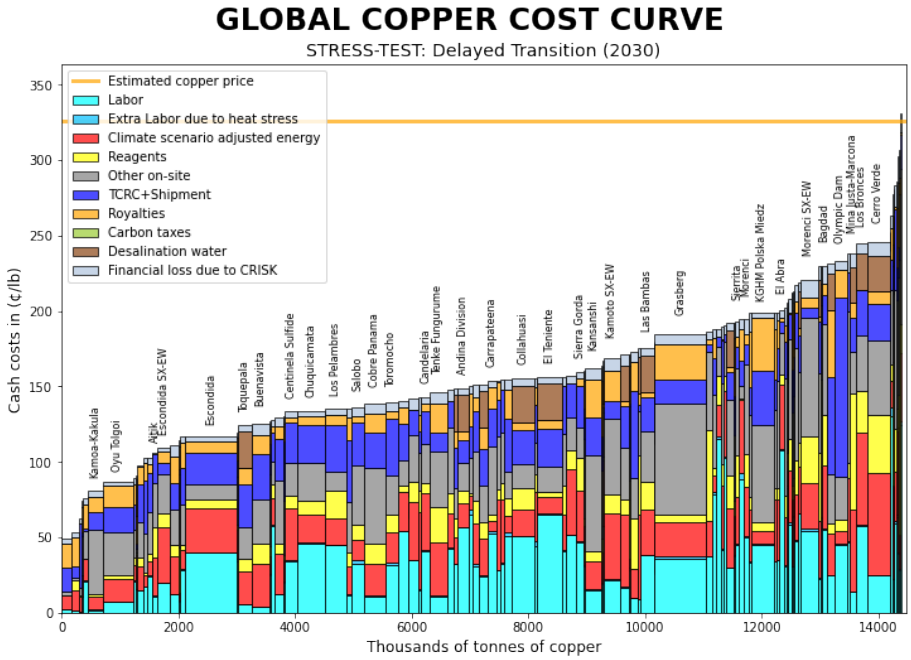


Figure 5.4: Global cost curve for primary copper producers - delayed transition scenario in year 2030. Own elaboration.

**Net zero 2050 - Year 2030**

The net zero 2050 scenario has significant variations in carbon pricing since the transitional risks are higher, resulting in a completely different cost curve, as seen in Figure 5.5. In this scenario physical risks have caused some mines to incur desalination and also to pay high carbon prices due to their emissions. Consequently, this have decreased their competitiveness significantly for some mines e.g.: Toquepala, El Teniente, Collahuasi, Los Bronces, Las Bambas, Cerro Verde, among others. As a result, the entire cost curve has increased. Moreover, the 50% percentile is around 175 cents per pound, while the 95% is around 280 cents.

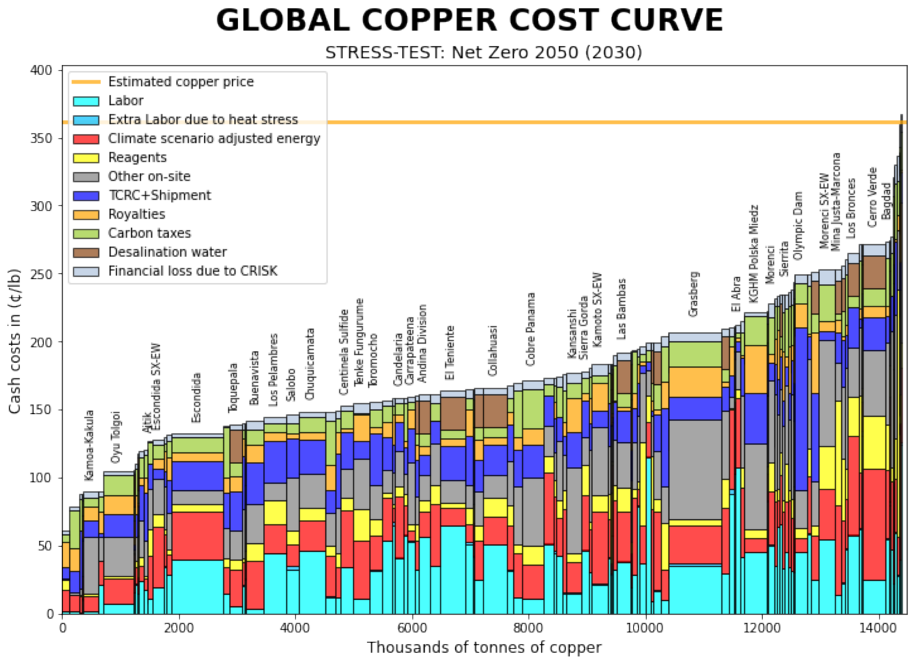


Figure 5.5: Global cost curve for primary copper producers - net zero 2050 scenario in year 2030. Own elaboration.

### Current policies - Year 2050

This scenario is the scenario with the highest physical risks, therefore the financial losses are the largest of the three, as is the number of mines that have to incur desalination. Similarly, there are lower labour costs due to lack of productivity due to climatic factors.

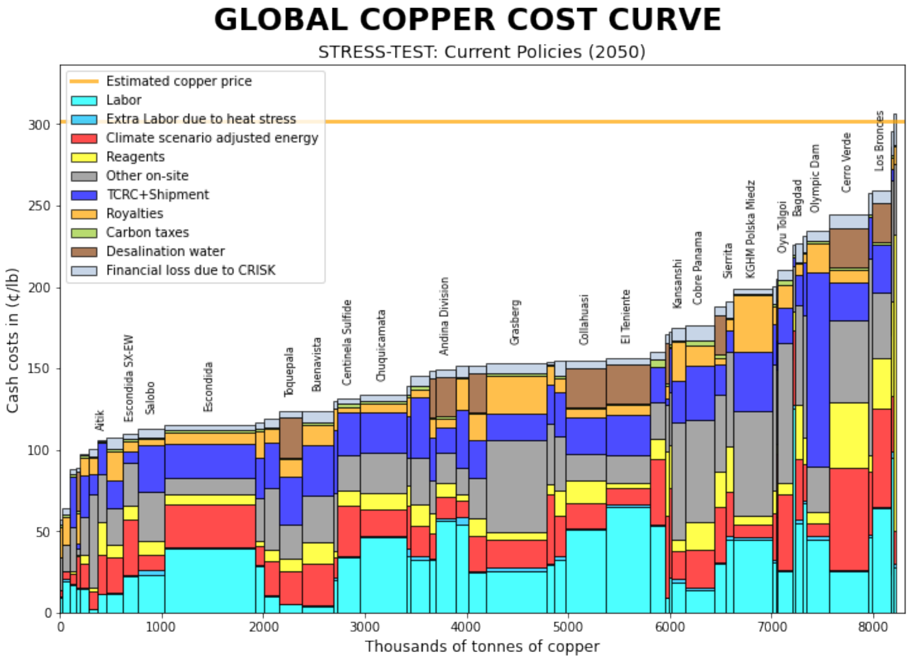


Figure 5.6: Global cost curve for primary copper producers - current policies scenario in year 2050. Own elaboration.

### Delayed transition - Year 2050

This scenario shows the late transition in which governments have committed to taking extreme measures to avoid the effects of climate change, raising carbon prices to exorbitant levels. This scenario certainly does not constitute a realistic scenario for the price of copper, as companies would react and the market would not fail. On the other hand, it provides an overview of the financial efforts that companies would have to make in order to facilitate the transition. The 50% percentile is at 300 cents per pound, while 95% is around 800 cents.

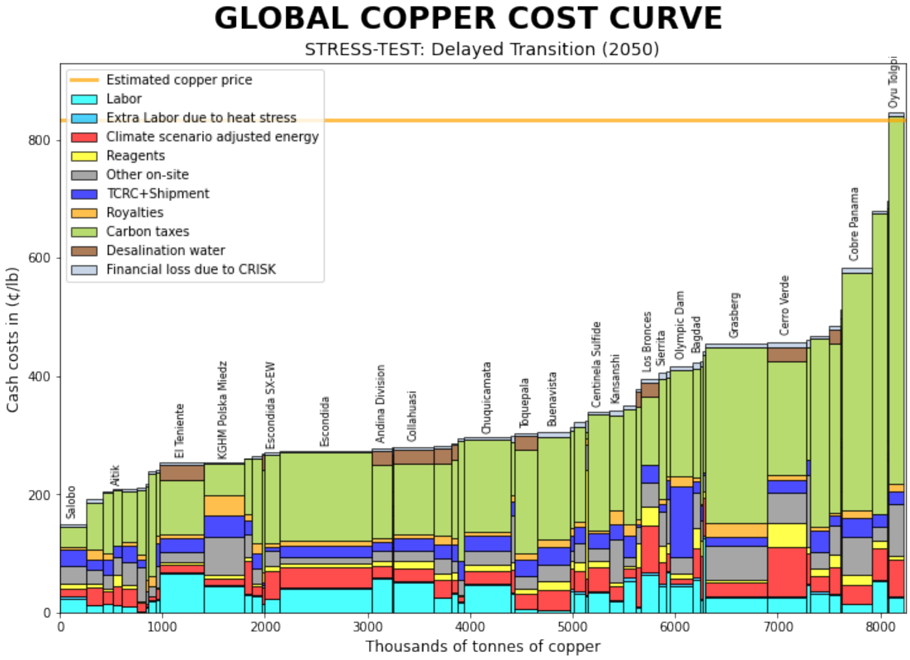


Figure 5.7: Global cost curve for primary copper producers - delayed transition scenario in year 2050. Own elaboration.

Figure 5.7 shows the mines most exposed to transition, such as Oyu Tolgoi, Cobre Panama, Cerro Verde, Grasberg, Olympic Dam, among others.

### Net zero 2050 - Year 2050

Finally, the scenario with lower physical risks shows a significantly higher cost curve, higher than the scenario with current policies, but lower than the late transition scenario. The 50% percentile is at 220 cents per pound, and 95% at 450 cents per pound. However, as mentioned above, this scenario does not reflect a realistic curve as companies are expected to react to these carbon prices by investing in new technologies.

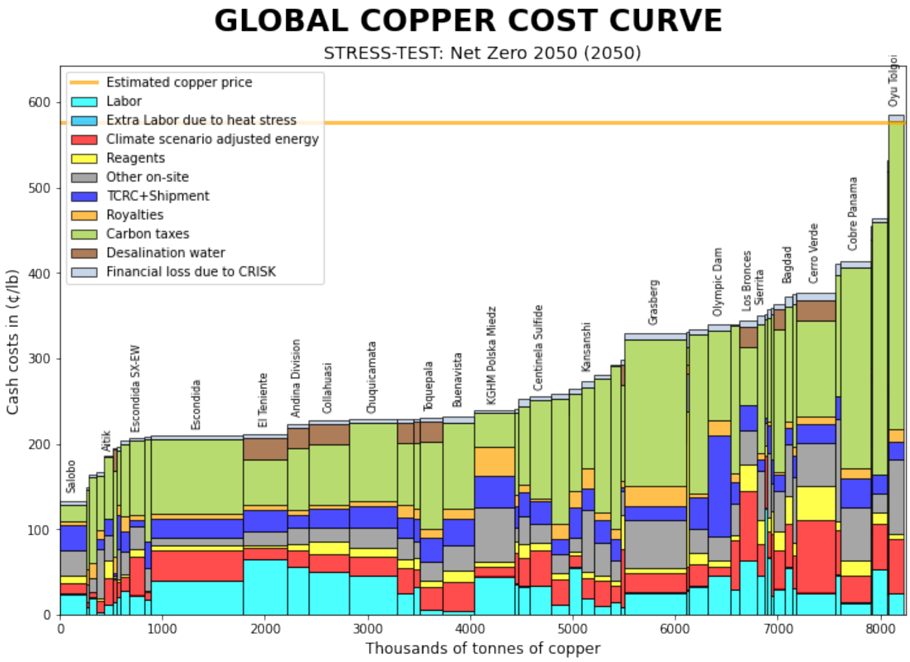


Figure 5.8: Global cost curve for primary copper producers - net zero 2050 scenario in year 2050. Own elaboration.

## 5.3.2 Country level cash costs

Cashcosts are analysed at a country level for each scenario and year of study. Looking ahead to 2030 there are almost imperceptible differences between current policy scenarios and late transition. However, the stress test reveals which countries are exposed to water stress and therefore their average costs are affected by this new factor. These countries include Mongolia, Chile, and Peru. In the same way, minimal differences can be observed in terms of extra labour due to heat stress, as well as financial losses due to climatic risks. Zambia and Indonesia are the hardest hit by the former, while regarding financial losses due to disruption of operations, it is observed that among the large producers, the Philippines, the United States and China are the most exposed. What can be clearly seen for this horizon in the Net Zero 2050 scenario, is the introduction to carbon taxes, from which relevant countries such as China, the United States, Panama and Kazakhstan are observed to be the most exposed. It is clear that the costs for each scenario change significantly for the 2050 timeframe. The current policy scenario is the one with the lowest costs out of the three. Financial losses have grown, as has extra labour as a result of greater physical risks. However, because carbon costs are much higher, physical risks take a second place. The cases of Indonesia, Mongolia, and Panama, which are over-exposed to carbon pricing, are particularly remarkable. Weakly exposed nations, such as DRC and Sweden, appear to profit from a scenario with high transition risks.

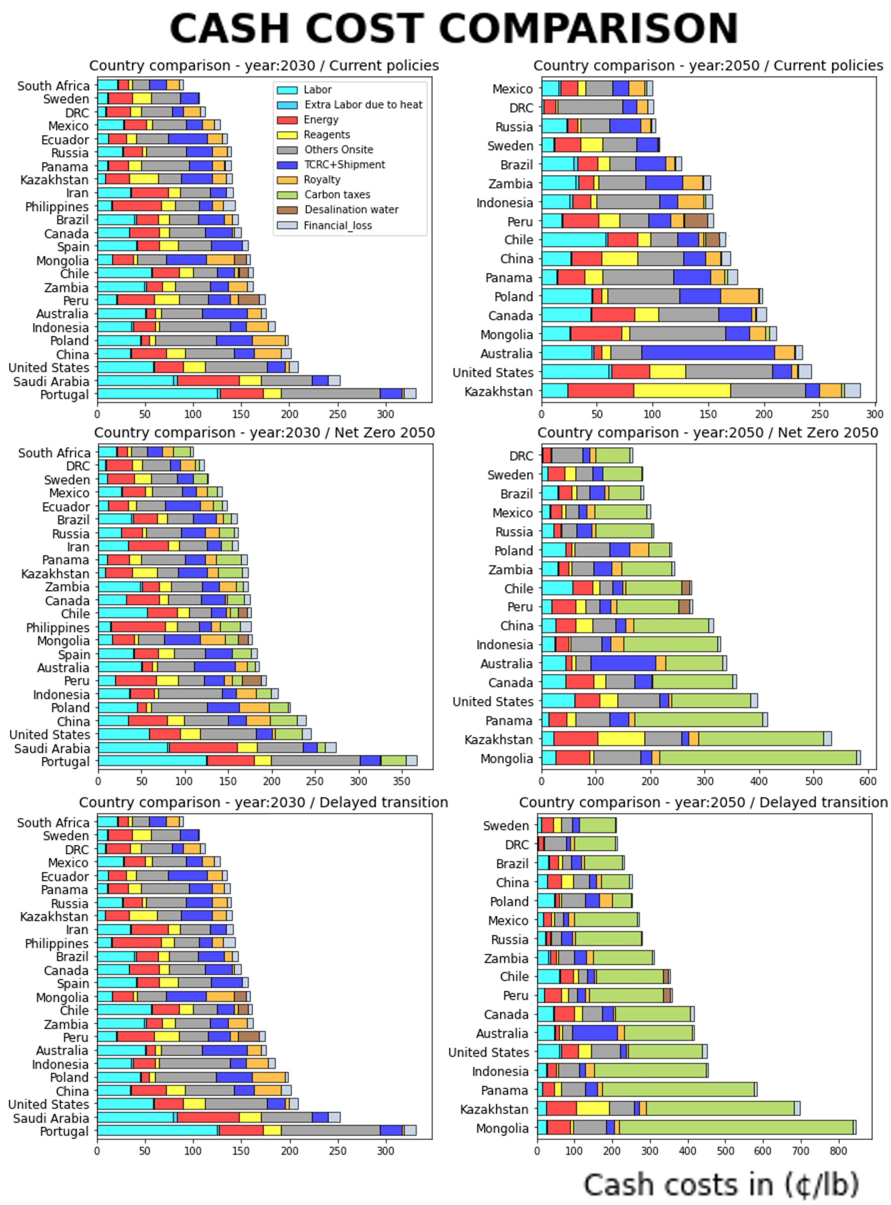


Figure 5.9: Global copper main producers mean country level cashcost under different climate scenarios and years. Own elaboration.

# Chapter 6

# Discussion

**Introduction**

The outcomes of the constructed model are discussed in this chapter. It moreover examines the implications for the commodity and potential steps that the actors will or should take to offset potential negative financial repercussions.

## 6.1 Stress-test of copper mining

### 6.1.1 The Results: Implications

Copper is a commodity that is essential to make the transition to a more environmentally friendly world, since it is a raw material for building electrified infrastructure. However, it has been observed from this study that copper itself must undergo a transition to ensure its production in the coming years. The stress test allows to detect the sensitivity of this commodity to the different types of climatic risks which were in turn adjusted to three of the climate scenarios established by NGFS. The synthesis of these results is shown in Figure 6.1. Moreover, greater sensitivity to transition risks than to physical risks in terms of the costs of this commodity can be noted from this figure. This is due that carbon pricing is a direct premium on top of producing costs. On the other hand, physical risks are considered as the potential financial loss due to disruption in operations and hence its effect on the overall yearly producing cost are less notorious. However, one of the observations mentioned repeatedly in this study is the fact that copper is a highly stressed commodity relative to water. Moreover, water stress, as stated previously, is a chronic physical risk that occurs despite the fact that the same region may experience more intense rainfall and associated floods. An example of this is the north of Chile, which is water-stressed, however, as reviewed in the case studies, also suffers from flooding. Therefore, the major risk is the need to desalinate, which increases costs significantly as it is very intensive in terms of energy use. This study also ignores the capital costs that this would include, as well as the repair costs due to climatic disasters – which should be given due consideration as well.

Figure 6.2 shows that in the short term there are minimal differences with respect to physical risks and the baseline, so the late transition and current policy scenarios are quite similar with these costs 5% and 5.3% higher than the

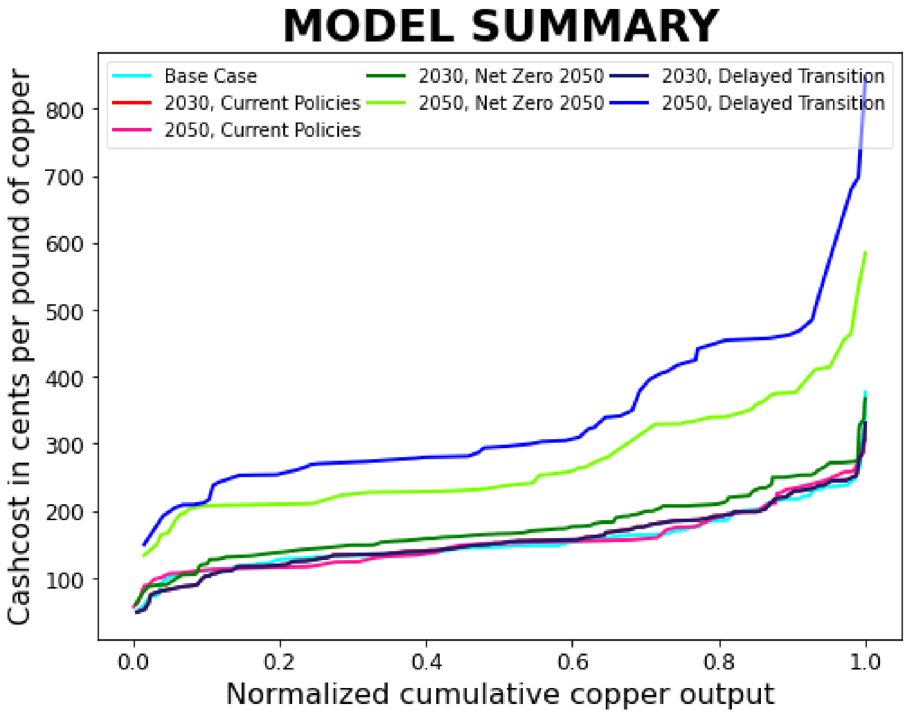


Figure 6.1: Model summary. Own elaboration.

baseline. The biggest divergences between scenarios are due to carbon prices. In this sense, making a transition from net zero to 2050 would mean increasing the overall costs of copper supply by about 18%. Among the notable companies, among the most affected in this horizon are Grasberg, Cobre Panama, Morenci, and Oyu Tolgoi. On the other hand, by 2030, it is expected that many companies will have to resort to desalination, reducing their profitability significantly. Toquepala, El Teniente, Collahuasi, and Cerro Verde are some of them.

In the short term, the disorder scenarios do not show large differences from the baseline (only 5%), however in the long term they are the ones that would have the greatest negative impact on this commodity (122. 2% increase to the baseline) – in this case the late transition scenario. In other words, this scenario would mean that mining companies would suddenly have to pay skyrocketing carbon prices in an attempt by governments to make drastic changes to reduce emissions and global warming by 2100. So these companies in the most likely scenario would have to either invest in technologies that lower their emissions or pay this tax with the risk of being over-exposed to the price of copper. On the other hand, from a government point of view, one would expect those companies to the right of Figure 4.17 – such as Oyu Tolgoi or Cobre Panama – to be under constant pressure to make such efforts and obtain their operating licenses. They would also face pressure from surrounding communities, which is another potential risk of disruption. As well, the financial sector and banks also put pressure on these companies by refusing loans, so one would expect the cost of capital to be higher under this scenario as there are fewer entities willing

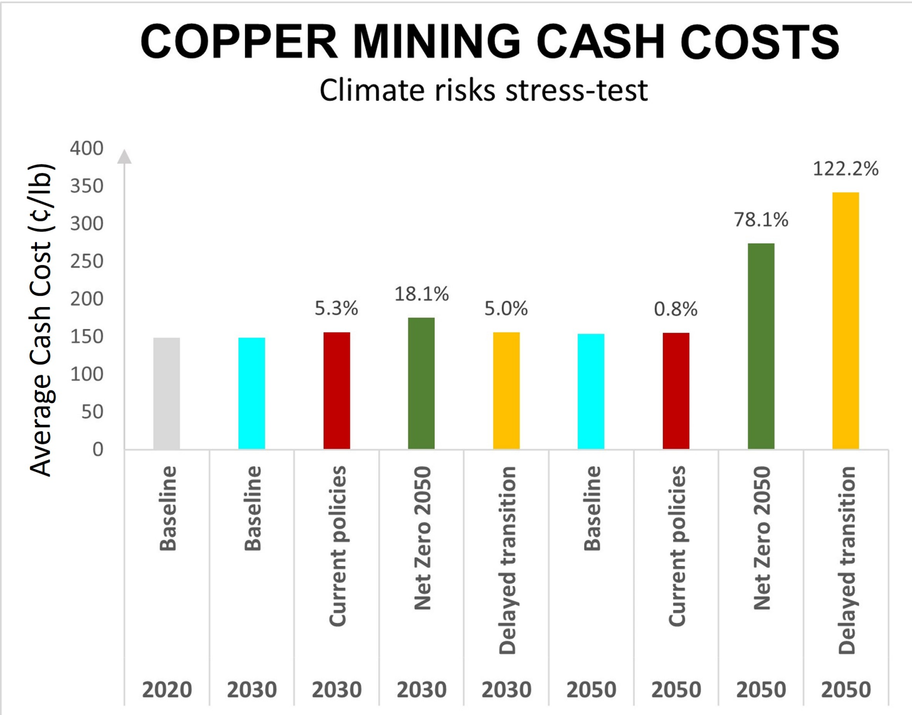


Figure 6.2: Global copper main producers carbon dioxide intensity versus supply curve. Own elaboration adjusted from CRU database.

to invest in these companies.

A Net Zero 2050 scenario in this case significantly reduces both physical and transition risks when compared to the Delayed Transition scenario. Furthermore, this scenario distributes transition risks over all years with the aim of ensuring that companies make an early transition so that physical risks do not develop over the coming years. This focus also reduces the negative financial effects of the carbon price as it increases over the years, so that, in this case, mines that did not make an early transition will have to pay more for their emissions the longer they delay in that transition.

Finally, the current policy scenario undergoes a slight change from the baseline, of 5.3% and 0.8% for 2030 and 2050 respectively. Based on the evidence presented in this study, it can be observed that copper mining is considerably more vulnerable to transition risks than to physical risks. Given this, companies in this area should react early in making the transition proactively to mitigate these risks.

### 6.1.2 About the model

The developed model is a static model that portrays the outcome if mining businesses carried on with "business as usual" operations and would not respond to market and regulation cues. This fact has both favorable and unfavorable characteristics when combined with the assumptions the model introduces. These are discussed in the following SWOT analysis:

**Strengths**

- The parameters used in the model are strong and they can be updated over time.
- Inter-linkage between parameters can be easily modified.
- Other factors such as new mines, LOM, grade distribution, new technologies, etc can be updated or integrated easily to the model. The models foundations are solid.
- The model allows to also examine the compensating effects of decisions and business as usual. For instance, it could be studied throughout this model if a specific mine is compensating productivity for the effect of heat stress.

**Weaknesses**

- Assumptions can be considered limiting and simplistic however this model intends to give rather an holistic reference for decisions instead of forecasting exact outcomes.
- If a realistic scenario is required, the static model may be of little use since it attempts to represent current gaps and the risks of not modifying

**Opportunities**

- The model is modular and can be adapted to new commodities or industries as well.
- The outcomes of this model can serve as benchmarks for institutions and governments to assess mines and identify dis-alignments in the industry.

**Threats**

- Fundamental changes in copper industry could be a threat, such as new exotic sources of copper, or copper substitutes. This would require to rethink the copper industry and therefore assumptions of this model will not longer be valid. However, given that mining is one of the industries thought to be lagging behind in terms of changes and disruptions, this threat may be unlikely.
- Ownership format as well as unchanged geopolitical scenario assumption is a threat, this could change and make the model obsolete. To mitigate this, the model requires to be regularly updated.

Therefore, this analysis proves that strengths and opportunities out weight the weaknesses and threats which leads to the fact that the model is useful and valid. To further enhance the model, weaknesses can be overcome by data consolidation, data mitigation, and understanding the linkages between the parameters. On the other hand, threats are either unlikely or not very significant, however, it is necessary to pay attention to potential changes that could change the foundations of the model.

## 6.2 The outlook for copper

### 6.2.1 The race for transition and copper as the key enabler

The Paris Agreement was made by 196 nations in 2015 at the COP21 United Nations Climate Change Conference. In comparison to pre-industrial levels, it attempted to "reduce global warming to far below 2 degrees Celsius, preferably below 1.5 degrees Celsius" (UN, 2015). In order to become carbon neutral by the middle of the century, countries must immediately reduce their emissions. At COP26 in Glasgow in 2021, that ambition was reaffirmed.

Bonakdarpour and Bailey (2022) mentions the United States has set decarbonization objectives that will increase copper consumption there. The United States outlined specific objectives for how it would keep global warming to 1.5 degrees Celsius in its Long-term Strategic planning to Net-Zero Greenhouse Gas Emissions by 2050, which was released in 2021. Similarly, the EU committed to reducing GHG by up to 55 percent by 2030 and becoming carbon neutral by 2050 in its European Green Deal. Nonetheless, the Commission has put out the REPowerEU proposal to wean Europe off from Russian fossil fuels by 2030 as a result of Russia's conflict in Ukraine. This plan aims for accelerating the use of renewable energy sources and the electrification of the economy.

One of the most crucial minerals for the energy shift is copper because it is one of the most effective electrical and thermal conductors available. Figure 6.3 shows that several important renewable technologies are expected to have high copper demand. In addition, copper-intensive traditional applications like electricity networks will grow over the next few decades. However, concerns have been raised about potential copper shortages since these technologies have a high copper intensity, hence demand for this metal is expected to grow significantly faster than supply.

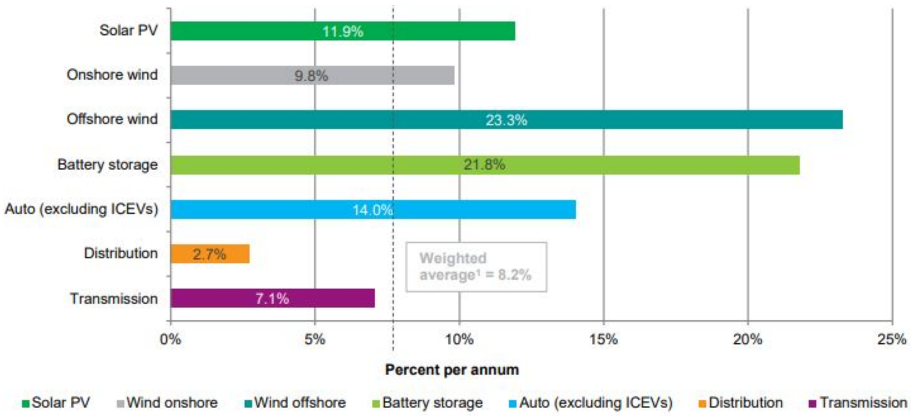


Figure 6.3: Gross copper demand compound annual growth rate for key energy transition applications. From Bonakdarpour and Bailey (2022).

It will take several years until 2050 to fully implement low-carbon power and automotive applications in order to achieve net-zero emissions. These technologies use more copper than their conventional counterparts, especially EVs and renewable energy sources like solar PV and wind turbines. To facilitate this electrification, investments in the electrical system are also essential. Bonakdarpour and Bailey (2022) notes by 2035 these industries will require an additional 12 MMt of copper annually. As a result, over that time period, these industries will experience double-digit annual growth rates in copper demand.

However, the global adoption of new technologies that depend on electricity rather than fossil fuels is necessary in order to reach the transition goal. Unfortunately, compared to conventional automobile and power technologies, energy transition-related technologies have a larger mineral intensity. Additionally, significant expenditures in upgrading and expanding the power grid infrastructure—which calls for more copper—will be necessary to electrify the economy.

### 6.2.2 Copper's own transition

The results of this study prove that climate risks pose a systemic risk to copper mining companies as well as to those who provide them with financing. Previously, a full chapter described the need of loans to finance both projects and operations for copper mining. With rising civil society expectations and an increasing number of mining businesses embracing the concept of sustainable inclusive development, multilateral and private investment agencies are becoming more careful about who, where, and when to fund. It is also worth noting that the banks' strategy today is centered on facilitating the shift to environmentally responsible businesses. As a result, the credits they grant will prioritize certain firms or industries. Those copper mines who do not opt to transition will face not only the risks discussed above, but also a lack of access to financial facilities and, as a result, a rise in costs of debt the more this transition is delayed. Bonakdarpour and Bailey (2022) notes that after the financial boost of the metal supply constraints in 2021, which drove prices nearly to historical levels, mining has been in good financial shape throughout the previous year. The author mentions the Ukrainian crisis has made this situation even more beneficial for miners by driving up the price of metals like copper and aluminum to record highs. Furthermore, despite the pandemic and the war in Europe, mining shareholders reportedly had unusual returns. Consequently, the source remarks that producers' balance sheets are stronger than ever and may be the outcome of strict financial management, industry-record margins, and strong market fundamentals.

Kettle (2022) raises concern that the time for these mining companies to transition to greener technologies has passed. The author points out that instead of pressing for large investment in the metals that will bring decarbonization, miners have been lately allocating money and concentrating their efforts on the carbon reduction of their operations in an effort to increase value to shareholders. These companies claim that they are upholding balance sheet integrity and fulfilling investors' demands. Moreover, Figure 6.4 displays the future expected scenario, with total capex expected to decrease by more than 70% by 2026, is even more alarming. Lacking lithium's involvement, the decline is considerably more pronounced, falling by more than 80% over the following five years. Lithium would be excluded, leaving investment at just 6% of 2012 levels in 2026. This scenario seriously jeopardizes the capacity to deliver the

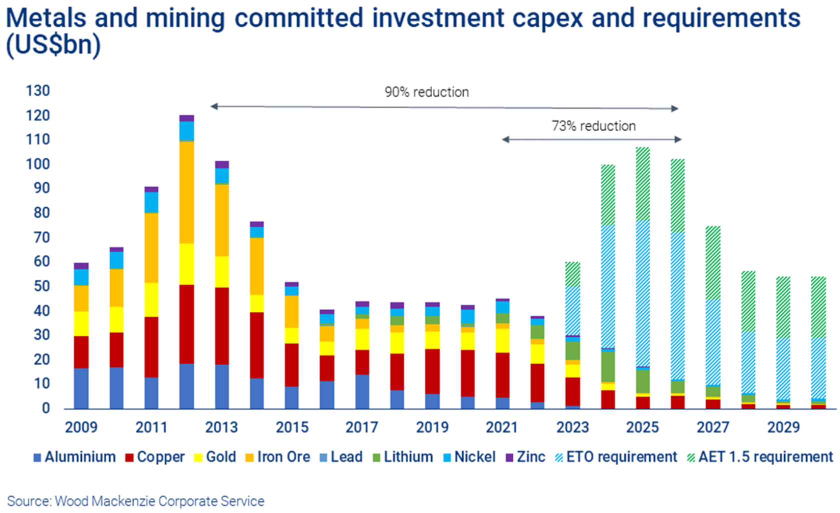


Figure 6.4: Metals and mining committed investment. From Kettle (2022).

metals required for the energy transition. Considering industry lead times, $400 billion needs to be raised by 2030, and it needs to be front-loaded. Everything appears, at best, improbable and, at worst, impossible.

New projects, on the other hand, will have to consider climate risks from the design stage, which may have an impact on discounted cash flows and, as a result, discourage investment in these projects because either the required Capex would be expected to be higher - given that such technologies tend require higher expenditures - or carbon prices simply consume production margins, causing this industry less attractive for investors. Furthermore, the findings of the stress test revealed that nations that were previously deemed high risk (especially in Africa, such as Congo and Zambia) turn out to be highly attractive due to their minimal exposure to climate risks, however, their high political risks may still offset their attractiveness. Moreover, it is relevant to note that around 50% of the copper supply from major copper producers such as Chile, Peru, Australia, and Indonesia is subject to high climate risks, particularly in a transition scenario (see Figure D.22 in Appendix). So we will have to look carefully at the agenda of these countries, as it may pose a risk to this commodity in the future.

## 6.3 Adoptions to counter climate risks

### 6.3.1 The carbon emissions mitigation road-map

It is evident from the findings and the discussion above that reducing carbon emissions will effectively bring carbon taxes to a reasonable amount, and thus prevent the main financial consequences of climate risks on mining in the long run. Consequently, mining companies may lower their risk of being affected by the carbon price by identifying the main sources of greenhouse gas emissions and taking steps to reduce them.

Energy-saving measures are the most effective strategy to lower greenhouse gas emissions.Although every mine is different, it is generally acknowledged that the majority of greenhouse gas emissions are caused by the use of fossil fuels for on-site energy, fugitive methane emissions, and transportation mineral ore to markets across the globe.

The main source of emissions on the copper supply curve is seen in Figure 4.17 where the 80–20 of them are mainly due to mineral processing, followed by mineral mining, and then downstream processing. The former uses electricity as a source primarily for grinding and crushing. The source of power therefore has a significant impact on emissions. In most mining operations, onsite fossil energy consumption accounts for nearly all greenhouse gas emissions. The mining sector primarily operates core mining and minerals processing processes, as well as mining haul trucks, mostly on fossil fuel-based diesel. Most of energy is utilized for comminution, material transportation, mineral ore separation/froth flotation, and underground mine ventilation. Blasting, drilling, dewatering, and operating mine site structures and crew housing need less total energy.

Smith (2013) has studied various measures that would significantly reduce emissions in the mining industry, for this particular study in Australia. These measures have been classified according to their emission reduction potential (X-axis), and their associated cost or savings (Y-axis). The width of the rectangles in turn indicates the extent of the potential savings of each measure. It also indicates the expected time for each measure to be taken.

This investigation demonstrates that improving power generation from thermal energy is one example of a short-term approach that would dramatically cut emissions. Mobile equipment equipment has the ability to cut operational expenses as well as pollution. Long term, important measures include the enhancement of mining equipment as well as the updating and efficiency of energy generating facilities. Figure 6.5 shows that improving the fuel efficiency of materials transportation through the use of in-pit crushers and conveyors (IPCC), conveyors, and electrifying haul trucks with "trolley assist" is the most profitable energy efficiency measure for mining companies in the short term. Subsidization of diesel fuel, in addition to the steps mentioned above that combat price volatility, employing alternative renewable energy sources, such as biodiesel, would greatly diminish the tax burden levied on fossil fuels.

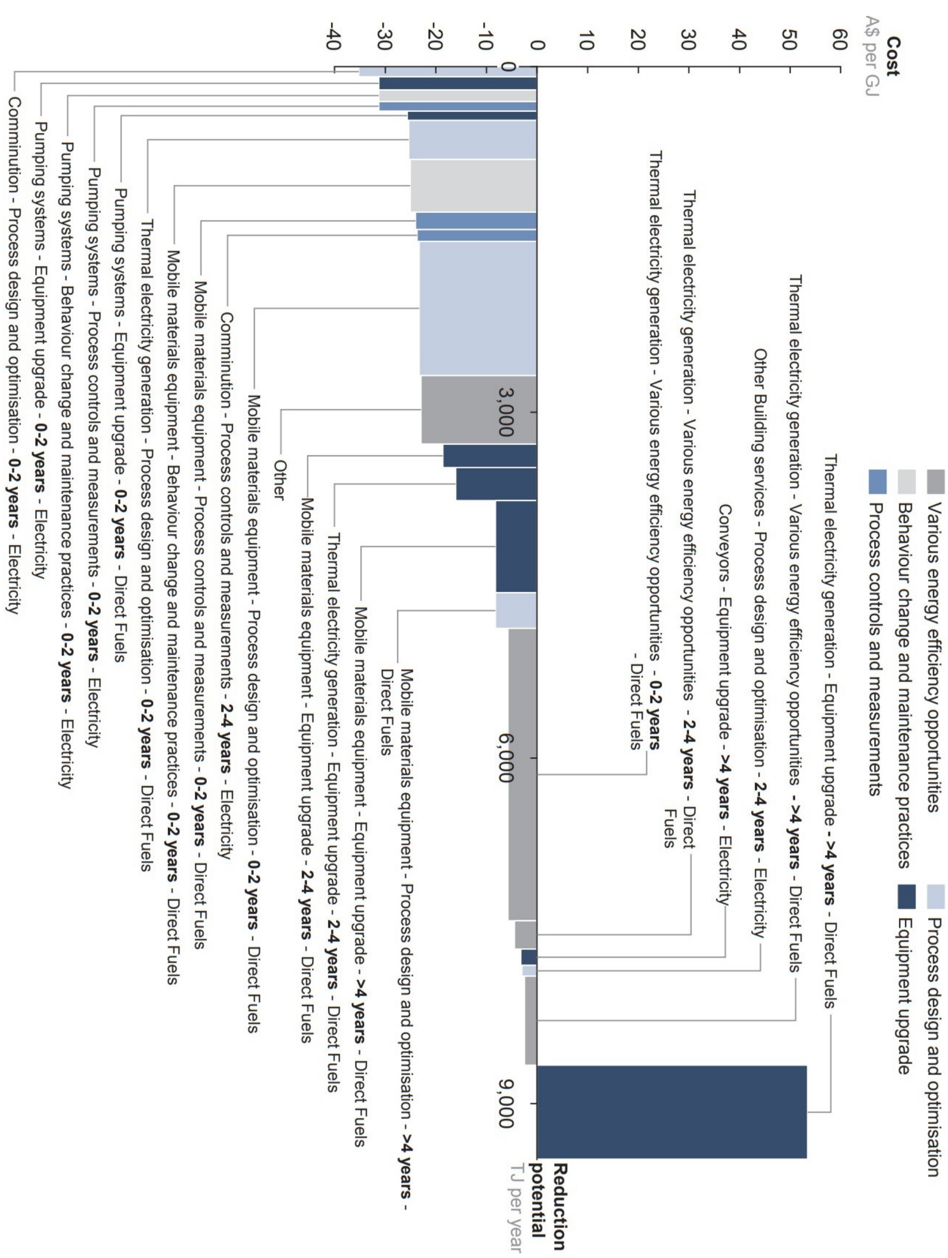


Figure 6.5: Energy efficiency opportunity cost curve – metal ore – open cut mining sector. From Smith (2013).

### 6.3.2 Engaging the water stress problem

Water stress ranks second in terms of financial impact, behind only the previously stated carbon prices. Mines under these conditions will be obliged to desalinate saltwater in order to continue operations. However, copper mines have limited options for considerably reducing their water usage in order to prevent desalination. Nonetheless, to improve resiliency, Delevingne et al. (2020) mentions some ways mine companies can reduce the water intensity of their mining processes by, for instance, recycling used water and reducing water loss from evaporation, leaks, and waste. Mining companies can prevent evaporation by putting covers on small and medium dams, however in the long term more capital-intensive approaches are also possible and likely to take place. New water infrastructure, such as dams and desalination plants, is expensive but sometimes necessary. Companies can also rely on so-called natural capital, like wetland areas, to improve groundwater drainage. The option of securing water rights is becoming harder and can take years of engagement because of increased competition for natural resources and tensions between operators and local communities.

The usage of fresh water in mining is being debated for which some mining companies are researching ways to drastically reduce or eradicate water consumption. A good example of this is Anglo American whom 75% of operations are in water stressed countries (AngloAmerican, 2022). This company is now working on the so called "the water-less mine" as one of their aspirational project part of the 4 axis of their strategy FutureSmart Mining. The project intents to "eliminate fresh water from mining processes, especially in the separation and transportation of ore and waste (tailings)". They will do so by:

1. Increasing water efficiency with a closed loop recycling system to absolutely minimise water losses by using the same water again and again. Today, this company meets two thirds of our total operational water requirements in this way.

2. Measuring evaporation rates to conserve more water. Evaporation losses in dams account for 10% to 25% of total water lost at a mine which accounts for water costs approximately US$200 million annually to replace. This technology has been used at their Dawson Mine, in Queensland Australia.

3. Using (Low-cost) Dry tailings disposal to limit water loss. Water sent to tailings disposal often represents the largest water loss at a mine. Essentially this is done by floating particles at sizes two to three times larger than normal making it easier to extract water from the process and leaving a waste stream that is dry and stackable.

4. Innovating with dry separation techniques that use less water. One example is to find new methods for dry comminution (the crushing and grinding, usually sequentially, of ore to the required particle size. The potential for a 30-40% reduction in water used per unit of mineral production, as well as the other benefits including increased production.

### 6.3.3 Physical risks mitigation

Those mines that are exposed to high physical risks have the option of transferring this risk to insurers- for instance, Teck buys insurance for extreme weather conditions. However, Nelson and Schuchard (2011) emphasizes that weather-related losses may result in higher insurance premiums or insurers rejecting to offer insurance or re-insurance. However, miners are not the only business that is exposed. Due to the increased frequency and severity of extreme weather events, insurers are reassessing how they approach providing coverage. A 30-year assessment of weather-related expenditures on different industries was done by S&P-Global (2021a). Figure 6.6 displays how, over the past 20 years, climate change has increased or made most of these events worse (70 percent in the previous 20 years).

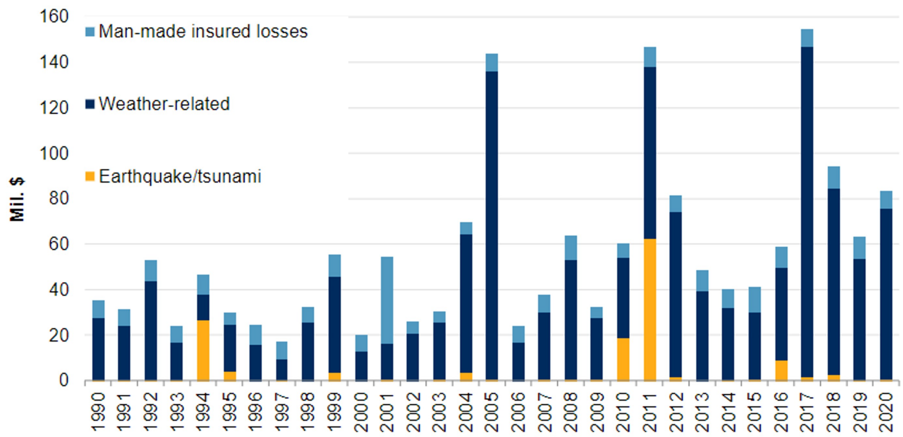


Figure 6.6: Insurers losses due to climate-related disasters. From (S&P-Global, 2021b).

Financial regulators are therefore starting to seek more transparency of climate-related risks and the inclusion of climate change in stress testing scenarios in various parts of the world. Give this, climate stress testing is becoming more common in many parts of the world, with eye-opening results for insurers as businesses and investors deal with the risks of climate change. Finally, S&P-Global (2021b) came to the conclusion that premium increases might reach 200 percent over the following 30 years.

Climate change settings and the lack of a coordinated industry-wide strategy to response may undermine investor confidence and, as a result, damage insurance dynamics across the mining sector in the long run. Mining plans in areas that are likely to become climatically susceptible over the next several decades, including those that may have already reached climate thresholds, will find less traction with insurers and investors. Climate change may cause the industry to seek adaptive strategies in order to retain its functions and lifespan.

Smith (2013) and Delevingne et al. (2020) have proposed different expected adoptions that mines will carry out to offset the effects of cyclones, extreme rainfall, and flooding:

- Increase design and construction standards. Surface drainage path designs should at least take into account 1 in 100 year 72 hour rainfall/flood event.

- Implementing non-trucking forms of transportation, such as by constructing a complete in-pit crushing and conveying system.
- Flood defence measures and putting in place flood-proof mining designs that enhance draining and pumping operations to deal with high-water issues as well as installing backup generators.
- Multiple transport routes or employing hard metal or crusted rock to improve dryness, or installing protected haul roads. A good example of road adaptations is what First Quantum Minerals did at its Sentinel copper mine in Zambia.
- Engagement with the government and contracting climate risks insurances.

On the other hand, some expected adoptions mines will undertake to mitigate heat stress and wildfires have been shared by Smith (2013):

- Heat stress and OHS disease exposure prevention plan
- Improve underground cooling systems as well as implementing energy efficient air-conditioning
- Improve bushfire management plan, build appropriate fire breaks, and work with Rural Fire Service

### 6.3.4 Skilled workforce migration and scarcity

Other forms of risks were observed, such as migration induced by a loss of food security in various mining locations. Peru, Zambia, and DRC, in particular, are vulnerable to this sort of risk due to a previously observed disparity between supply and demand for these commodities. In these mining regions, the consumption of wheat is very large and important negative impacts of climate change are expected, implying the need to adapt to large production gaps. On the other hand, according to the case studies previously reviewed, tensions between mining firms and landowners have been rising as water stress increases. However, it is indeed crucial for mining corporations to come to agreements with farmers on water use since complications with food security and scarcity can put labour shortages in mines at risk. Nelson and Schuchard (2011) mentions in order to mitigate reputational risks and to meet needs of all users, community water infrastructure and watershed restoration projects may be required. Moreover, the author mentions there may be opportunity for more meaningful engagement with local communities and other key stakeholders, particularly regarding collaboration on land, agriculture, and water management.

Neglecting these factors could endanger mining operations since less personnel is willing to work and live in these remote and increasingly tough regions. This effect may raise overall labour costs since companies will have to improve working conditions to maintain this industry attractive to workers in the future, which will certainly have an impact on the cost curve. As per the literature review, these risks have not yet been linked to mining. However, such a proper investigation is suggested.

# Chapter 7

# Conclusions and recommendations

Finally, taking into account the results of this study, it is possible to proceed on to answering the research questions presented at the initial phase of this study:

- **What will be the impact of climate risks on copper mining operations?**
  Due to the overall water crisis, many major global copper producers in Chile and Peru, will have to rely on seawater desalination, assuming current technologies. This significantly raises production costs, and the price of copper is expected to be affected equally. Water use is critical not only for mining operations, which primarily for minerals beneficiation, but also for the agricultural industry and surrounding communities. Since a large portion of copper production occurs in water-stressed areas, tensions between these actors have been rising. However, research is being conducted to identify processing pathways in the absence of water.

  Similar to water scarcity, increasing food shortages driven on by global warming will compromise food security in many areas. This could lead to the mining companies' already scarce labour migrating to other, more amenable areas, making it harder for the sector to find workers and raising the cost of labour to both attract and retain them.

- **What is the outlook for copper producers under different climate scenarios?**
  The simulation of copper mining under different climate scenarios revealed that climatic risks are a systematic risk for mining companies, with 50% of the supply being at high risk. Furthermore, the simulation through all the scenarios demonstrates that copper producers are significantly more vulnerable to transition risks than physical risks. Moreover, in scenarios with a high risk of transition, mining companies are more vulnerable if these policies are implemented in a disorderly manner (Delayed Transition) than if they were applying Net Zero 2050 policies. Results show that high transition scenarios could bring current costs of production up to +18.1% and +122% in 2030 and 2050 respectively.

For this reason, mines should be able to reconcile an early transition to carbon neutral technologies since they would otherwise be overexposed. On the other hand, the disparity between the required and actual committed investments indicates that this is an unlikely scenario.

- **How would climate change affect mines' finances and copper supply under different climate scenarios?**
  The above partially answered this research question. What was mentioned previously creates a conflict as financial institutions will provide fewer credits to polluting companies and industries that are not aligned with their green agenda. As a result, copper mining finances will be affected since the longer it takes these companies to transition, the more challenging it will be for them to finance it whilst paying higher interests to finance current operations and also paying potential carbon prices that are expected to increase.

  Interestingly, results, on the other hand, also showed that large producers in countries that were previously considered unattractive for investment - e.g. as Zambia and DRC - proved low exposure to climate risks. This may cause financial institutions and investors to reconsider investing in these countries, as they are also expected to have competitive advantages in terms of production costs to their peers.

  The gap between demand for copper required for the transition and the expected supply of copper in the future poses a severe risk. This is expected to be a barrier for the transition since copper is a key enabler in producing the infrastructure required for a carbon-neutral world.

- **Recommendations**
  A stress test on copper mines throughout the globe under various climatic conditions was made possible by the model's ability to integrate a wide range of data sources. However, due to the overall model's simplicity, its conclusions can only be used as a guide for potential consequences on the copper sector. Given that certain mines are better equipped than others to handle such disasters, it would be crucial for future studies to take into account how exposed each specific mine is to physical risks as assuming that all mines are equally vulnerable is a model flaw.

  The methodology used in this work also makes this tool scalable to other commodities, particularly those of interest that are more harmful for the environment than copper, including aluminum and steel. Therefore, it is encouraged to keep developing this tool and look at different sectors or metals.

# Chapter 8

# Bibliography


Andela, N., Morton, D., Giglio, L., and Randerson, J. (2019). Global fire atlas with characteristics of individual fires, 2003-2016. https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1642. NASA. Retrieved on: 08-06-2022.

AngloAmerican (2022). Picture this: the water-less mine. https://www.angloamerican.com/futuresmart/stories/our-industry/technology/picture-this-the-waterless-mine. Retrieved on: 22-05-2022.

Aquino, M. and Cambero, F. (2021). Analysis: In world's top copper region political risk rises. https://www.reuters.com/world/americas/worlds-top-copper-region-political-risk-rises-2021-05-17/. Retrieved on: 25-03-2022.

Aquino, M. and Cambero, F. (2022). Will chile move to nationalize lithium and copper mines https://www.thedialogue.org/analysis/will-chile-move-to-nationalize-lithium-and-copper-mines/. Retrieved on: 25-03-2022.

Arndt, N., Fontboté, L., Hedenquist, J., Kesler, S., Thompson, J., and Wood, D. (2017). *Future Global Mineral Resources*, volume 6, pages 1–171. Geochemical Perspectives.

Assan, J. and Rosendelf, T. (2012). *Environmentally induced migration, vulnerability and human security: consensus, controversies and conceptual gaps for policy analysis*, volume 24. Journal of International Development.

Attwood, J. and Biesheuvel, T. (2021). Water scarcity is starting to bite in biggest copper supplier. https://www.bloomberg.com/news/articles/2021-08-18/chile-environmental-court-to-hear-case-against-bhp-copper-mine. Retrieved on: 25-03-2022.

Balch, O. (2014). Mongolia's water scarcity could threaten its economic boom. https://www.theguardian.com/sustainable-business/mongolia-water-scarcity-threaten-economic-boom-mining. The Guardian. Retrieved on: 16-06-2022.

Bauwens, J. (2016). Landslide at Kamoto copper mine kills at least two. https://sciencythoughts.blogspot.com/2016/03/landslide-at-kamoto-copper-mine-kills.html?m=0. Sciency Thoughts. Retrieved on: 16-06-2022.

Benning, I. (2000). *Bankers' perspective of mining project finance*, volume 100, pages 145–152. The Journal of The South African Institute of Mining and Metallurgy.

BIS (2021). *Climate-related financial risks – measurement methodologies*, pages 1–50. Bank for International Settlements. Basel Committee on Banking Supervision report.

BNAmericas (2011). Escondida reanuda operaciones gradualmente mientras mejoran condiciones climáticasr. https://www.bnamericas.com/es/noticias/escondida-evacua-a-trabajadores-y-suspende-todas-las-operaciones. BNAmericas. Retrieved on: 13-06-2022.

BNAmericas (2022). Mineras de chile recurren al agua de mar en medio de menores leyes. https://www.bnamericas.com/es/reportajes/mineras-de-chile-recurren-al-agua-de-mar-en-medio-de-menores-leyes. Retrieved on: 25-06-2022.

Bonakdarpour, M. and Bailey, T. (2022). The future of copper: Will the looming supply gap short-circuit the energy transition? https://www.spglobal.com/en/research-insights/featured/copper-on-the-rise#:~:text=The%20Future%20Of%20Copper%3A%20Will,Net%20Zero%20Emissions%20by%202050. S&P Global. Retrieved on: 06-08-2022.

Brychcy, M., Dec, M., and Thys, T. (2020). *Desalination is not the only answer to Chile's water problems.* McKinsey and Company.

Camiper (2022). Extracción de agua en mina cerro colorado prohibida por tribunal ambiental de chile. https://camiper.com/tiempominero-noticias-en-mineria-para-el-peru-y-el-mundo/extraccion-de-agua-en-mina-cerro-colorado-prohibida-por-tribunal-ambiental-de-chile/. Tiempo Minero. Retrieved on: 13-06-2022.

Cheff, I.; Nistor, I. and Palermo, D. (2018). *Pedestrian evacuation modelling of a Canadian West Coast community from a near-field Tsunami event*, pages 343–353. Springer Nature B.V.

Cochilco. (2022). Informe de tendencias del mercado del cobre. https://www.cochilco.cl/Mercado%20de%20Metales/Informe%20de%20Tendencias%20Mercado%20del%20Cobre%20Q4%202021%20Ver.%20Final.pdf. Retrieved on: 23-03-2022.

Codelco (2016). Codelco división el teniente suspende operaciones como consecuencia del severo evento climático. https://www.codelco.com/codelco-division-el-teniente-suspende-operaciones-como-consecuencia-del/prontus_codelco/2016-04-16/215608.html. Retrieved on: 16-06-2022.

Codelco (2022a). Division andina. https://www.codelco.com/andina. Retrieved on: 22-03-2022.

Codelco (2022b). Division andina. https://www.codelco.com/gabrielamistral. Retrieved on: 22-03-2022.

Cong, Y. (2021). Global near real-time daily apparent temperature and heat wave dataset (2006-2020). https://zenodo.org/record/4764325. Zenodo. Retrieved on: 08-06-2022.

Cox, D., Lindsey, D., Singer, D., Moring, B., and Diggles, M. (2007). *Sediment-Hosted Copper Deposits of the World: Deposit Models and Database*. USGS.

Darling, P. (2011). *SME Mining Engineering Handbook*, pages 11–62. Society for Mining, Metallurgy, and Exploration.

Dasgupta, S., Maanen, N., Gosling, S., Piontek, F., Otto, C., and Schleussner, C. (2021). *Effects of climate change on combined labour productivity and supply: an empirical, multi-model study*, volume 5, pages 455–465. Elsevier Science & Technology.

Delevingne, L., Glazener, W., Gregoir, L., and Henderson, K. (2020). *Climate risk and decarbonization: What every mining CEO needs to know*. McKinsey and Company.

Denina, C. and Reid, H. (2021). Big miners reconsider congo, zambia risks as copper price surges. https://www.reuters.com/article/mining-copper-risk-idUSKBN2H31IQ. Retrieved on: 25-03-2022.

DMP (2019). The dangers of working in high-heat environments. http://www.dmp.wa.gov.au/News/The-dangers-of-working-in-high-26280.aspx. Government of Western Australia Department of Mines, Industry Regulations, and Safety. Retrieved on: 24-06-2022.

DMP (2021). Rio tinto fined after workers exposed to extreme conditions. https://www.dmp.wa.gov.au/News/Rio-Tinto-fined-after-workers-29744.aspx. Government of Western Australia Department of Mines, Industry Regulations, and Safety. Retrieved on: 24-06-2022.

Elderson, F. and Breeden, S. (2020). Guide to climate scenario analysis for central banks and supervisors. https://www.ngfs.net/sites/default/files/medias/documents/ngfs_guide_scenario_analysis_final.pdf. Network for greening the financial system. Retrieved on: 21-03-2022.

Energiminas (2020). Concentradora de mina justa procesará 750 toneladas de mineral cada hora y con agua de mar. https://energiminas.com/concentradora-de-mina-justa-procesara-750-toneladas-de-mineral-cada-hora-y-con-agua-de-mar/. Retrieved on: 16-06-2022.

Ernst and Young (2021). Top 10 business risks and opportunities for mining and metals in 2022. https://www.ey.com/en_gl/mining-metals/top-10-business-risks-and-opportunities-for-mining-and-metals-in-2022. Ernst & Young. Retrieved on: 15-04-2022.

Escobar, A. (2015). Pobladores cortan suministro de agua a minera buenavista del cobre. https://olca.cl/articulo/nota.php?id=105190. Observatorio Latinoamericano de Conflictos Ambientales. Retrieved on: 16-06-2022.

Finneran, M. (2010). Wildfires: A symptom of climate change. https://www.nasa.gov/topics/earth/features/wildfires.html. NASA. Retrieved on: 26-05-2022.

Fitch-Ratings (2022). Fitch ratings raises global metals and mining price assumptions. https://www.fitchratings.com/research/corporate-finance/fitch-ratings-raises-global-metals-mining-price-assumptions-21-03-2022. Retrieved on: 25-03-2022.

Fitch-Solutions (2021). Global copper mining outlook. https://www.fitchsolutions.com/commodities/global-copper-mining-outlook-29-06-2021. Retrieved on: 17-03-2022.

Fitch-Solutions (2022). Zambia's short-term political outlook positive, but long-term risks persist. https://www.fitchsolutions.com/country-risk/zambias-short-term-political-outlook-positive-long-term-risks-persist-03-03-2022. Retrieved on: 25-03-2022.

Frei, M. (2005). *Composition, formation, and leaching behaviour of supergene, polymetallic ores from the Sanyati deposit (Zimbabwe): A case study*. PhD thesis, Technische Universität Berlin.

Garcia, N. (2017). Analisis economico de aspectos asociados a la desalinizacion del agua en la mineria. https://www.camara.cl/verDoc.aspx?prmID=114031&prmTIPO=DOCUMENTOCOMISION. Biblioteca del congreso nacional de Chile. Retrieved on: 05-05-2022.

Gassert, F., Luck, M., Landis, P., Reig, and Shiao, T. (2013). Aqueduct global maps 2.0. https://www.wri.org/data/aqueduct-global-maps-20. World Resources Institute. Retrieved on: 26-05-2022.

GM (2006). Peru's antamina mine reopens after shutdown. https://www.theglobeandmail.com/report-on-business/perus-antamina-mine-reopens-after-shutdown/article4108929/. The Globe and Mail. Retrieved on: 24-06-2022.

Haselgrove, S. (2020). Cyclone damien disrupts degrussa operations. https://safetowork.com.au/cyclone-damien-disrupts-degrussa-operations/. Safetowork.com. Retrieved on: 16-06-2022.

Hassanpour, S. and Senemari, S. (2015). *Mineralogy and Geochemistry Studies of the Sorkheh Sediment-hosted Stratiform Copper (SSC) Deposit, NW Iran*, volume 7, pages 89–105. Islamic Azad University Mashhad Branch.

Hjort, J., Streletskiy, D., Dore, G., Wu, Q., Bjella, K., and Luoto, M. (2022). *Impacts of permafrost degradation on infrastructure*, volume 3, pages 24—-38. Nature Reviews Earth  Environment.

Horton, J. and Mancini, M. (2008). How landslides work. https://science.howstuffworks.com/environmental/earth/geology/landslide3.htm. HowStuffWorks. Retrieved on: 26-05-2022.

Howes, N. (2020). Heavy rains unleash deadly landslide onto myanmar mine, killing at least 160. https://www.theweathernetwork.com/ca/news/article/heavy-rains-unleash-deadly-landslide-onto-myanmar-mine-hpakant-kachin-state. Retrieved on: 26-05-2022.

Iannucci, E. (2022). Rain and covid dull oz minerals' shine. https://www.miningweekly.com/article/rain-and-covid-dulls-oz-minerals-shine-2022-04-22. Mining Weekly. Retrieved on: 16-06-2022.

ICSG (2014). Copper bulletin. https://copperalliance.org/wp-content/uploads/2012/01/ICSG-Factbook-2014.pdf. The International Copper Study Group. Retrieved on: 08-06-2022.

ICSG (2021). The world copper factbook 2021. https://icsg.org/wp-content/uploads/2021/11/ICSG-Factbook-2021.pdf. The International Copper Study Group. Retrieved on: 14-03-2022.

Jamasmie, C. (2018). Leagold closing brazil mine for two months due to drought. https://www.mining.com/leagold-closing-brazil-mine-two-months-due-drought/#:~:text=Canada's%20Leagold%20Mining%20(TSX%3ALMC,the%20country's%20Minas%20Gerais%20State. Mining.com. Retrieved on: 22-05-2022.

Jamasmie, C. (2021). Chile's drought forces antofagasta to cut copper guidance. https://www.mining.com/chiles-drought-forces-antofagasta-to-cut-copper-guidance/. Retrieved on: 25-03-2022.

John, D., Ayuso, R., Barton, M., Blakely, R., Bodnar, R., Dilles, J., Gray, Floyd, Graybeal, F., Mars, J., McPhee, D., Seal, R., Taylor, R., and Vikre, P. (2010). *Porphyry deposits*. USGS. chap. B of Mineral deposit models for resource assessment: U.S. Geological Survey Scientific Investigations Report 2010–5070–B. Retrieved on: 14-03-2022.

Kenton, W. (2020). Debt-to-ebitda ratio. https://www.investopedia.com/terms/d/debt_edbitda.asp#:~:text=What%20Is%20the%20Debt%2Dto,%2C%20depreciation%2C%20and%20amortization%20expenses. Investopedia. Retrieved on: 22-04-2022.

Kettle, J. (2022). Have miners missed the boat to invest and get ahead of the energy transition? https://www.woodmac.com/news/opinion/have-miners-missed-the-boat-to-invest-and-get-ahead-of-the-energy-transition/. Wood Mackenzie. Retrieved on: 14-07-2022.

Kirschbaum, D. (2018). Global landslide catalog. https://data.nasa.gov/Earth-Science/Global-Landslide-Catalog/h9d8-neg4. NASA. Retrieved on: 29-05-2022.

Kosich, D. (2010). Wildfire creeps closer to capstone mining's minto mine. https://www.proactiveinvestors.co.uk/companies/news/73161/wildfire-creeps-closer-to-capstone-minings-minto-mine-6327.html. Mineweb.com. Retrieved on: 31-05-2022.

Krause, V. (2021). Iso 3166-1/2 boundary polygons. https://www.volkerkrause.eu/2021/02/13/osm-country-subdivision-boundary-polygons.html. Volker Krause. Retrieved on: 08-06-2022.

Krzak, M. (2021). *Is the EU's Resource Base of Copper Ore Deposits Large? A Fuzzy Set Theory Approach*. MDPI.

Lilford, E. and Guj, P. (2020). *Different types of mineral royalties*, chapter 4, pages 43–69. Springer.

LME (2022). London metal exchange rules and regulations. https://www.lme.com/-/media/Files/Clearing/Rules-and-regulations/LME-Clear-rules-and-procedures-July-2021.pdf. London Metal Exchange. Retrieved on: 14-07-2022.

Loboguerrero, A., Campbell, B., Cooper, M., Hansen, J., Rosenstock, T., and Wollenberg, E. (2019). *Food and earth systems: priorities for climate change adaptation and mitigation for agriculture and food systems*. MDPI.

Lou, E. (2017). Canada wildfires disrupt industry, force 14,000 from homes. https://www.reuters.com/article/us-canada-wildfire-idUSKBN19V23X. Routers. Retrieved on: 26-05-2022.

Mackenzie, W. and Cusworth, N. (2007). *The use and abuse of feasibility studies*. Project Evaluation Conference. AusIMM Project Evaluation Conference, Australasian Institute of Mining and Metallurgy.

Malambo, L. (2014). Management of heat underground. case study of deeps section at mopani copper mines mufulira mine site. https://www.grin.com/document/416767t. Grin. Retrieved on: 16-06-2022.

Mareels, S., Moore, A., and Vainberg, G. (2020). *Through-cycle investment in mining*. McKinsey and Company.

Maslin, M. (2020). Will three billion people really live in temperatures as hot as the sahara by 2070? https://www.ucl.ac.uk/news/2020/may/opinion-will-three-billion-people-really-live-temperatures-hot-sahara-2070. University College London. Retrieved on: 13-06-2022.

McMichael, C. (2013). *Environmental deterioration and human health*, chapter Climate change and migration: food insecurity as a driver and outcome of climate change-related migration. Springer Nature B.V.

Merzdorf, J. (2020). Climate change could trigger more landslides in high mountain asia. https://climate.nasa.gov/news/2951/climate-change-could-trigger-more-landslides-in-high-mountain-asia/. NASA. Retrieved on: 26-05-2022.

Metso:Outotec (2020). Trends and forecasts within the copper market. retrieved from trends and forecasts within the copper market. https://www.mogroup.com/insights/blog/mining-and-metals/trends-and-forecasts-within-the-copper-market/. Retrieved on: 17-03-2022.

Mining.com (2021). Chinese investment in overseas copper projects just beginning. https://www.mining.com/charts-chinese-investment-in-overseas-copper-projects-just-beginning/. Retrieved on: 22-08-2022.

MiningJournal (2021). Bc miners eye impacts as more flooding, landslides forecast. https://www.mining-journal.com/leadership/news/1421921/bc-miners-eye-impacts-as-more-flooding-landslides-forecast. Retrieved on: 16-06-2022.

Murphy, C. (2020). Debt-to-ebitda ratio. https://www.investopedia.com/terms/n/netdebt.asp#:~:text=were%20due%20immediately.-,Net%20debt%20shows%20how%20much%20cash%20would%20remain%20if%20all,term%20and%20long%2Dterm%20debt. Investopedia. Retrieved on: 22-04-2022.

Narang, A. (2022a). All china-operated mines across the world are getting shut down. https://tfiglobalnews.com/2022/03/28/all-china-operated-mines-across-the-world-are-getting-shut-down/. TFI Global News. Retrieved on: 22-08-2022.

Narang, A. (2022b). Congo kicks out chinese company from one of the world's biggest copper-cobalt mining sites. https://tfiglobalnews.com/2022/03/02/congo-kicks-out-chinese-company-from-one-of-the-worlds-biggest-copper/. TFI Global News. Retrieved on: 22-08-2022.

Nelson, J. and Schuchard, R. (2011). Adapting to climate change: A guide for the mining industry. https://www.bsr.org/reports/BSR_Climate_Adaptation_Issue_Brief_Mining.pdf. BSR. Retrieved on: 26-05-2022.

NGFS (2022). Climate impact explorer. https://climate-impact-explorer.climateanalytics.org/. NGFS. Retrieved on: 08-06-2022.

Ngugi, B. (2022). Floods disrupt production at kwale titanium mines. https://www.businessdailyafrica.com/bd/corporate/industry/floods-disrupt-production-at-kwale-titanium-mines-3841530. Business Daily Africa. Retrieved on: 16-06-2022.

NI43-101 (2011). Standards of disclosure for mineral projects. https://mrmr.cim.org/media/1017/national-instrument-43-101.pdf. Canadian Securities Administrators. Retrieved on: 22-05-2022.

Norland, E. (2022). Five reasons copper prices have risen. https://www.institutionalinvestor.com/article/b1xs6f3jvrrcjg/five-reasons-copper-prices-have-risen. Institutional Investor. Retrieved on: 22-08-2022.

Northey, S., Haque, N., Lovel, R., and Cooksey, M. (2014). *Evaluating the application of water footprint methods to primary metal production systems*, volume 69, pages 65—80. Minerals Engineering.

Northey, S., Haque, N., and Mudd, G. (2013). *Using sustainability reporting to assess the environmental footprint of copper mining*, volume 40, pages 118–128. Journal of Cleaner Production.

Northey, S., Mudd, G., Werner, T., Jowitt, S., Haque, N., Yellishetty, M., and Weng, Z. (2017). *The exposure of global base metal resources to water criticality, scarcity and climate change*, volume 44, pages 109–124. Global Environmental Change.

NWS (2020). What is the heat index? https://www.weather.gov/ama/heatindex. National Weather Service. Retrieved on: 30-05-2022.

OCC (1998). Loan portfolio management handbook. https://www.occ.gov/publications-and-resources/publications/comptrollers-handbook/files/loan-portfolio-management/pub-ch-loan-portfolio-mgmt.pdf. Comptroller of the Currency Administrator of National Banks. Retrieved on: 12-05-2022.

Onepng (2022). Landowners disconnect water supply to png's ok tedi mining ltdr. https://www.onepng.com/2022/02/landowners-disconnect-water-supply-to.html. One Papua New Guinea. Retrieved on: 16-06-2022.

Oszczepalski, S., Speczik, S., Zieliński, K., and Chmielewski, A. (2019). *The Kupferschiefer Deposits and Prospects in SW Poland: Past, Present and Future.* Polish Geological Institute-National Research Institute.

Otto, J., Andrews, C., Cawood, F., Dogget, M., Guj, P., Stermole, F., Stermole, J., and Tilton, J. (2006). *Mining royalties: a global study of their impact on investors, government, and civil society.* The World Bank.

Ozcan, A. and Strauss, E. (2018). *New urban agenda: climate refugees and international responsibilities*, volume 7, chapter 4. International Journal of Structural and Civil Engineering Research.

Palmer, J. (2020). A slippery slope: Could climate change lead to more landslides? https://eos.org/features/a-slippery-slope-could-climate-change-lead-to-more-landslides. Eos, science news by AGU. Retrieved on: 26-05-2022.

Petley, D. (2020). The deadly landslide at the carmen copper mine in the philippines. https://blogs.agu.org/landslideblog/2020/12/24/carmen-copper-mine-1/. Retrieved on: 26-05-2022.

Pierre-Louis, K. (2022). A recipe for climate disaster: Extreme rain, rising sea levels, and more frequent wildfires are all making landslides more likely. https://www.theatlantic.com/science/archive/2022/03/climate-change-heavy-rain-landslides-flood/629404/. The Atlantic. Retrieved on: 26-05-2022.

Pollon, C. (2021). 'this mine dodged a bullet': massive b.c. landslide exposes new era of climate risks. https://thenarwhal.ca/bc-mines-landslide-climate-risk/. The Narwhal. Retrieved on: 26-05-2022.

Reuters (2007a). Floods hit output at zambia's mufulira copper mine. https://www.reuters.com/article/mufulira-floods-idUKL0103180320070501. Retrieved on: 16-06-2022.

Reuters (2007b). Kazakhmys says copper south mine restarts after flood. https://www.reuters.com/article/kazakhmys-copper-idUSL1442752020071214. Retrieved on: 16-06-2022.

Reuters (2015). Ok tedi png copper mine output stalled by low river water. https://www.reuters.com/article/copper-papua-idUSL5N1082AE20150728. Retrieved on: 16-06-2022.

Reuters (2019). Southern copper reinicia parcialmente operaciones en sur de perú afectada tras intensas lluvias. https://www.reuters.com/article/mineria-peru-southerncopper-idLTAKCN1Q11I5. Retrieved on: 15-06-2022.

Reyes-Bozo, L., Godoy-Faundez, A., Herrera-Urbina, R., Higueras, P., Salazar, J., Valdes-Gonzalez, H., Vyhmeister, E., and Antizar-Ladislao, B. (2014). *Greening Chilean copper mining operations through industrial ecology strategies*. Elsevier Science & Technology.

Rodriguez, P. (2021). Chinese mining and indigenous resistance in ecuador. https://carnegieendowment.org/2021/09/20/chinese-mining-and-indigenous-resistance-in-ecuador-pub-85382. Carnegie Endowment. Retrieved on: 13-06-2022.

Ruttinger, L. and Sharma, V. (2016). *Climate change and mining: A Foreign Policy Perspective*. Adelphi Research Gemeinnützige GmbH.

Scott, D., Bebbington, A., and Frey, K. (2018). *Mining and climate change: A review and framework for analysis*, volume 5. The Extractive Industries and Society.

Shen, Y. (2016). Chemical fate studies of mining reagents: Understanding the decomposition behavior under various conditions. https://academiccommons.columbia.edu/doi/10.7916/D8DV1SMB/download. Columbia University. Retrieved on: 08-03-2022.

Sierpińska-Sawicz, A. and Bak, P. (2015). *Costs of corporate bond issue in coal mining companies*, volume 10, pages 99–112. Contemporary Economics.

Sillitoe, R. (2009). *Porphyry Copper Systems*, volume 105, pages 3–41. Economic Geology.

Singer, D. (2017). *Future copper resources*, volume 86, chapter Renewable and Recycling. Ore Geology Reviews.

Skidmore, Z. (2021). Teck resources resumes operations at highland valley copper mine. https://www.mining-technology.com/news/teck-resources-copper-wildfires/. Mining Technology. Retrieved on: 31-05-2022.

Smith, E. (2021). Copper is 'the new oil' and low inventories could push it to $20,000 per ton, analysts say. https://www.cnbc.com/2021/05/06/copper-is-the-new-oil-and-could-hit-20000-per-ton-analysts-say.html. Retrieved on: 17-03-2022.

Smith, M. (2013). Assessing climate change risks and opportunities for investors. https://www.aph.gov.au/DocumentStore.ashx?id=a0874f61-5b76-48fd-9d55-2c785007cde6. Australian National University. Retrieved on: 28-05-2022.

SMM (2019). Landslide operation in grasberg mine is not affected. https://news.metal.com/newscontent/100917636/Landslide-operation-in-Grasberg-mine-is-not-affected/. SMM News. Retrieved on: 16-06-2022.

S&P-Global (2021a). Global reinsurers grapple with climate change risks. https://www.spglobal.com/ratings/en/research/articles/210923-global-reinsurers-grapple-with-climate-change-risks-12116706. Retrieved on: 12-05-2022.

S&P-Global (2021b). Mine economics methodology. https://spglobal.force.com/s/article/Mine-Economics-MethodologyCorpOverheads. Retrieved on: 04-05-2022.

SRK (2022). Kinsevere copper project: Due diligence in the drc. https://www.srk.com/en/publications/kinsevere-copper-project-due-diligence-in-the-drc. Retrieved on: 22-03-2022.

Surran, C. (2015). Newmont mining resumes gold processing at australian mine. https://seekingalpha.com/amp/news/2280026-newmont-mining-resumes-gold-processing-at-australian-mine. Newmont Corporation. Retrieved on: 14-06-2022.

Swissinfo (2017). Minas de cobre de chile suspenden operaciones por temporal. https://www.swissinfo.ch/spa/afp/minas-de-cobre-de-chile-suspenden-operaciones-por-temporal/43241942. Retrieved on: 13-06-2022.

Tarver, E. (2020). Exposure at default (ead). https://www.investopedia.com/terms/e/exposure_at_default.asp#:~:text=Exposure%20at%20default%20(EAD)%20is,to%20estimate%20respective%20EAD%20systems. Investopedia. Retrieved on: 23-04-2022.

Taylor, C., Causey, J., Denning, P., Hammarstrom, J., Hayes, T., Horton, J., Kirschbaum, M., Parks, H., Wilson, A., Wintzer, N., and Zientek, M. (2010). *Descriptive models, grade-tonnage relations, and databases for the assessment of sediment-hosted copper deposits: with emphasis on deposits in the Central Africa Copperbelt, Democratic Republic of the Congo and Zambia.* USGS.

UH (2017). Heatwaves: Number of deadly heat days. https://geoxc-apps.bd.esri.com/MoraLabs/GlobalRiskOfDeadlyHeat/index.html. University of Hawaii at Manoa. Retrieved on: 01-06-2022.

UN (2015). The paris agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. United Nations. Retrieved on: 06-08-2022.

UN (2022). Secretary-general calls latest ipcc climate report 'code red for humanity', stressing 'irrefutable' evidence of human influence. https://press.un.org/en/2021/sgsm20847.doc.htm#:~:text=Today's%20IPCC%20Working%20Group%201,of%20people%20at%20immediate%20risk. United Nations. Retrieved on: 06-08-2022.

Warner, K., Hamza, M., Oliver-Smith, A., Renaud, F., and Julca, A. (2010). *Climate change, environmental degradation and migration*, volume 55, pages 689—-715. Natural Hazards.

Wellmer, F., Dalheimer, M., and Wagner, M. (2008). *Economic evaluations in exploration*, chapter Economic Evaluations, pages 123–169. Springer Nature B.V.

Williams, F., McColl, S., Fuller, I., Massey, C., Smith, H., and Neverman, A. (2021). *Intersection of fluvial incision and weak geologic structures cause divergence from a universal threshold slope model of landslide occurrence*, volume 389. Elsevier Science & Technology.

WITS (2021a). Copper; bars, rods and profiles, of refined copper imports by country in 2021. https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2021/tradeflow/Imports/partner/WLD/product/740710#. World Integrated Trade Solution. Retrieved on: 23-03-2022.

WITS (2021b). Copper ores and concentrates exports by country in 2019. https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2019/tradeflow/Exports/partner/WLD/product/260300. World Integrated Trade Solution. Retrieved on: 17-03-2022.

WITS (2021c). Copper ores and concentrates imports by country in 2021. https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2021/tradeflow/Imports/partner/WLD/product/260300#. World Integrated Trade Solution. Retrieved on: 23-03-2022.

WITS (2021d). Copper; unrefined, copper anodes for electrolytic refining imports by country in 2021. https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2021/tradeflow/Imports/partner/WLD/product/740200#. World Integrated Trade Solution. Retrieved on: 23-03-2022.

WMO (2022). Number of wildfires forecast to rise by 50% by 2100e. https://public.wmo.int/en/media/news/number-of-wildfires-forecast-rise-50-2100#:~:text=Climate%20change%20and%20land%2Duse,according%20to%20a%20new%20report. World Metereological Organization. Retrieved on: 31-05-2022.

Zhuang, Y., Xing, A., Jiang, Y., Sun, Q., Yan, J., and Zhang, Y. (2022). *Typhoon, rainfall and trees jointly cause landslides in coastal regions*, volume 298. Elsevier Science & Technology.

# Appendices

# Appendix A

# Introduction

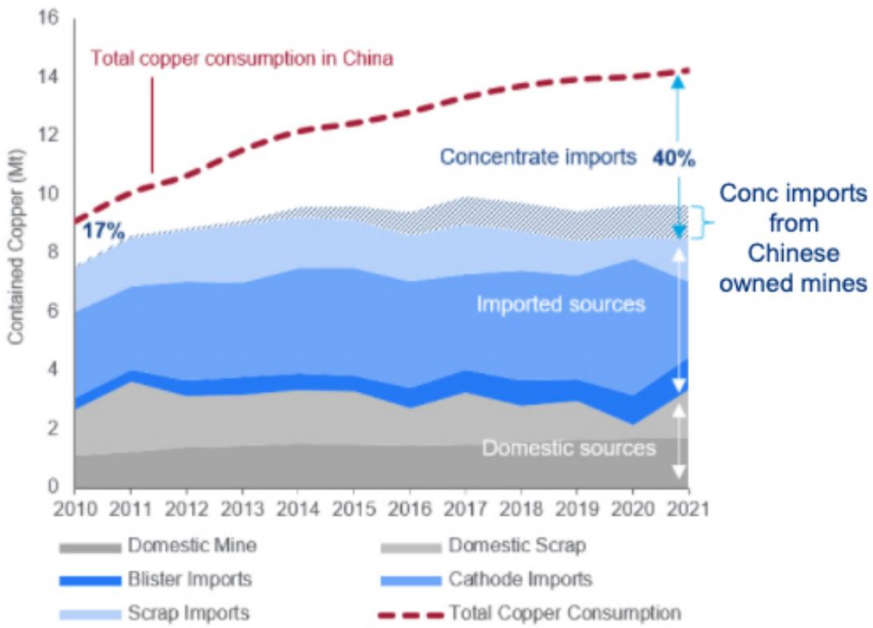


Figure A.1: China's copper concentrate requirements. From Mining.com (2021).

# Appendix B

# Climate scenarios input data

### Physical risks input

Within this category, and of all the parameters offered by NGFS, 15 relevant parameters were selected for this study. Each of these parameters will be used to correct the baseline to obtain “adjusted indexes” for each climate scenario. These are detailed below:

**Labour productivity due to heat stress:** The influence of heat stress on labour productivity is the rate drop in performance during regular working hours in warm and humid environmental conditions, as a result of the human body’s reduced capacity undertake physical labour.

**Fraction of population annually exposed to wildfire:** this parameter indicates the land surface portion inside a 0.5° precision grid cell that is ignited by wildfires at least once a year on average, multiplied by the total population of that grid cell.

**Fraction of population annually exposed to heatwaves:** in a grid cell of 0.5° resolution, this parameter shows the proportion of the population in that grid cell that suffers a heatwave on average each year. When both a relative indication based on air temperature and an absolute indicator based on air temperature and relative humidity surpass extraordinarily high values, a heatwave is deemed to occur.

**Air temperature:** this parameter is referred to as air temperature (2 metres above the ground in this case). The values employed have been subjected to a bias-adjustment process to account for differences between simulated and observed values across the time period in which they overlap.

**Precipitation:** this variable is defined as the amount of water (rainfall and snowfall) that falls on the Earth’s surface in a given region and period. The data for this parameter have been subjected to a bias-adjustment process to account for differences between simulated and observed values across the time period in which they overlap.

**Relative change in wind speed:** this parameter accounts for the velocity of the air mass. The wind speed 10 metres above surface is factored here. The data for this variable have been subjected to a bias-adjustment process to account for differences between simulated and observed values across the time frame in which they coincide.

**Change in land fraction annually exposed to river floods:** this metric is defined as the average land area percentage inundated during the year's most extreme flood. A flood is deemed to occur in a given place if the yearly maximum river discharge surpasses the FLOPROS database's local protection standard.

**Change in land fraction annually exposed to wildfires:** this value represents the land area percentage within a 0.5° grid cell that is burned by wildfires at least once a year on average.

**Relative change in river flood depth:** This parameter is considered as the flood depth reached during the year's most severe flood. Only if the yearly maximum discharge exceeds the local protection standard from the FLOPROS database is a flood determined to occur in a given location.

**Relative change in river discharge** this metric measures the change of the volume of water flowing through a river or stream channel.

**Relative change in surface runoff:** surface runoff (also known as overland flow) is the flow of water that occurs on the Earth's surface when surplus water, such as precipitation, cannot be absorbed by the soil.

**Relative Humidity:** the ratio of water vapour in the air to the entire quantity that might be retained at its present temperature is defined as this variable (saturation level). NGFS considers relative humidity at 2 meters above ground in this case. The data for this variable have been subjected to a bias-adjustment process to account for differences between simulated and observed values across the time period in which they overlap.

**Maize, wheat, rice, soy yield:** these yields were computed using the assumption that the farmed areas of rainfed and irrigated wheat, soy, rice, and maize will stay constant throughout the twenty-first century. As a result, their anticipated changes solely reflect the future evolution of climate, not agricultural management approaches.

**1-in-100-year expected damage from tropical cyclones:** this metric is expressed in 2005 US dollars and is defined as the degree of damage caused by such catastrophes that are statistically projected to occur once every 100 years.

### Transitional risks input

#### Carbon price

Each of the scenarios provide different trajectories of carbon prices - as displayed Figure 4.18, each country has its own specific carbon price for every scenarios which are implemented in the model.

The ideal mitigation trajectory, according to NGFS, with a greater carbon price in the first few decades and a slower rate of growth in the latter decades, may give the best possible choice to mitigate physical risks; this is the net-zero scenario. Nevertheless, for larger physical risk scenarios, the carbon price curve compresses, rather than flattening. The graph represents the change in carbon pricing when incorporating the median and 95th percentile damages for temperature rise in each time period. It is worth noting that cost rises related to carbon pricing cause a demand shock since they raise total production costs. Negative effects on demand are countered in orderly situations by higher government expenditure of carbon tax revenues.

In Net Zero 2050, the consequences of transition risk on global GDP are somewhat positive since the negative effects on demand from higher carbon pricing and energy costs are more than compensated by the recycling of carbon revenues into government investment and reduced employment taxes. The GDP repercussions of disorderly scenarios are negative because the pace of the change, along with investment uncertainty, reduces consumption and investment. Inevitably, the consequences are greater for nations and areas facing bigger emissions cuts, higher carbon pricing, decreased fossil fuel exports, or higher physical risk damages.

Across several countries, the adoption of carbon pricing in transition scenarios boosts energy costs in the short term, resulting in moderate rises in inflation and unemployment before reverting to previous trends. Opposing positive growth benefits from carbon revenue recycling lead to a decrease in unemployment in some countries and time frames.

**Price of energy**

As mentioned above, carbon prices have a direct effect on emissions on producers' finances, but they also have an indirect effect, as power generators also pay carbon prices, thus passing these costs on to their customers. This will generate in different scenarios a variation in the price of energy that will undoubtedly have effects on mining, since as we saw earlier, it is an energy-intensive industry. The price of energy varies on the location of the mine as well as the climate scenario. Overall it is expected that the short-term effect is an increase in the unit cost of production. This is will lead to inflation and unemployment from a macroeconomic point of view until it return to previous trends. NGFS mentions that recycling policies of pre-carbon revenues in some countries will have the effect of cushioning unemployment.

**Productivity**

The third and last transitional risk to be included in this model is labour productivity. It is expected under different scenarios that productivity varies according to environmental conditions, where humidity, environmental phenomena, or natural disasters will lead to material impacts on the economy and society, inducing a lower efficiency in productive work. NGFS provides a value for each country where the mines are located for each climate scenario.

These NGFS inputs were generated using existing climate models, which provide a simplistic, hence flawed, picture of the evolution of climate systems with regard to natural and human anthropogenic factors. Since a limited number of climate model simulations were used to generate them, short-term changes may represent the effect of natural climatic variability rather than the reaction to human global warming, disregarding NGFS's attempts to compensate for it as pre-processing the data. The conclusions' reliability reduces at high warming levels, which have been obtained in a fewer number of the climate model simulations supporting these findings, and notably for 2.5-3°C of global warming.

# Appendix C

# Mining Financials

## I Cashflows

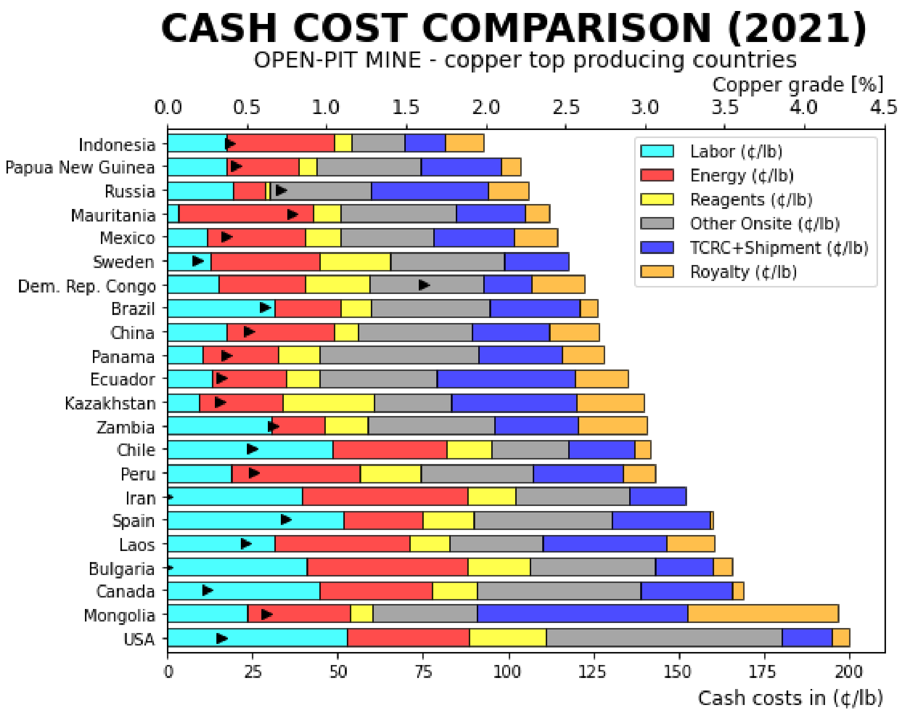


Figure C.1: Cashcost for Open-pit mines per country.

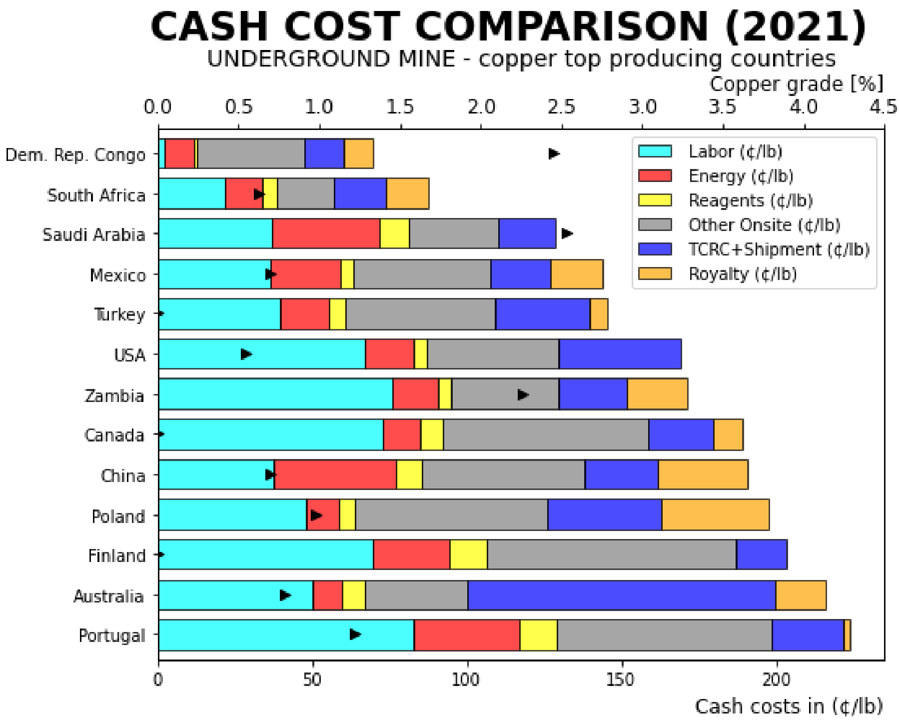


Figure C.2: Cashcost for Open-pit mines per country.

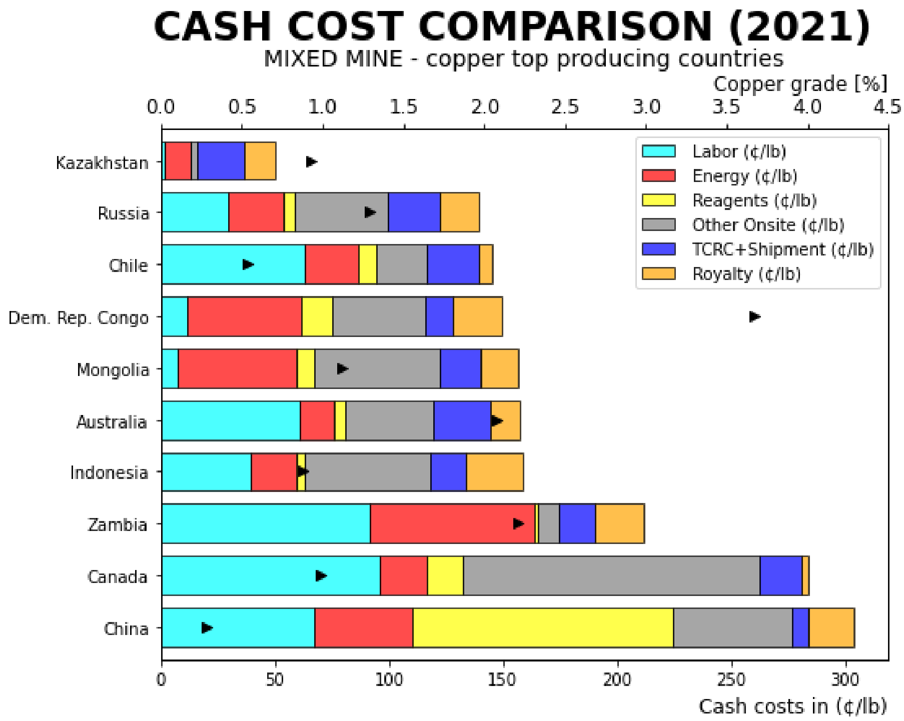


Figure C.3: Cashcost for Open-pit mines per country.

# Appendix D

# Climate Risks

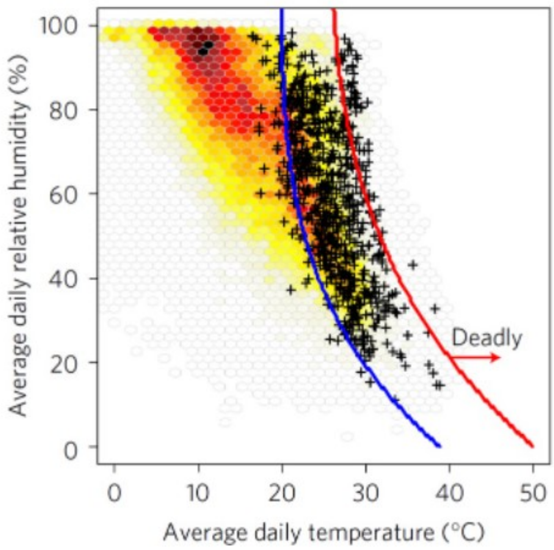


Figure D.1: Heat stress number of days in a year when conditions of temperature and humidity surpass that threshold and thus pose a risk of death. Blue line is the threshold that best separates times in the studied cities when conditions where lethal or not. The red-arrow is a threshold that yielded a 100% certainty on heatwaves being lethal, when it was surpassed. From UH (2017)

# I Physical risks overview


Figure D.2: Global mining climate-physical risks. From Delevingne et al. (2020).

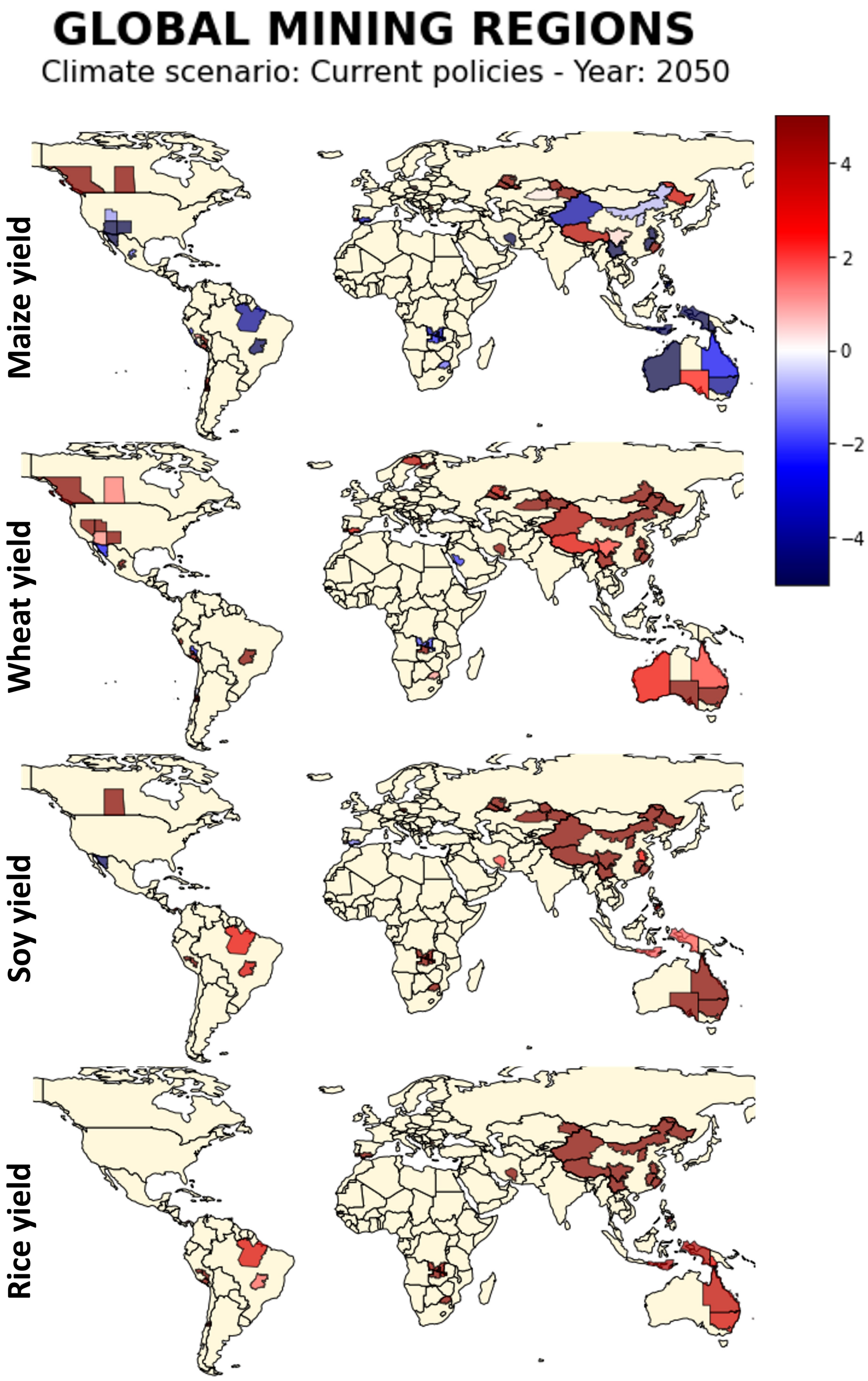


Figure D.3: Copper mining regions and expected food security development for 2050 under current policies. Own elaboration based on NGFS Climate Scenarios.

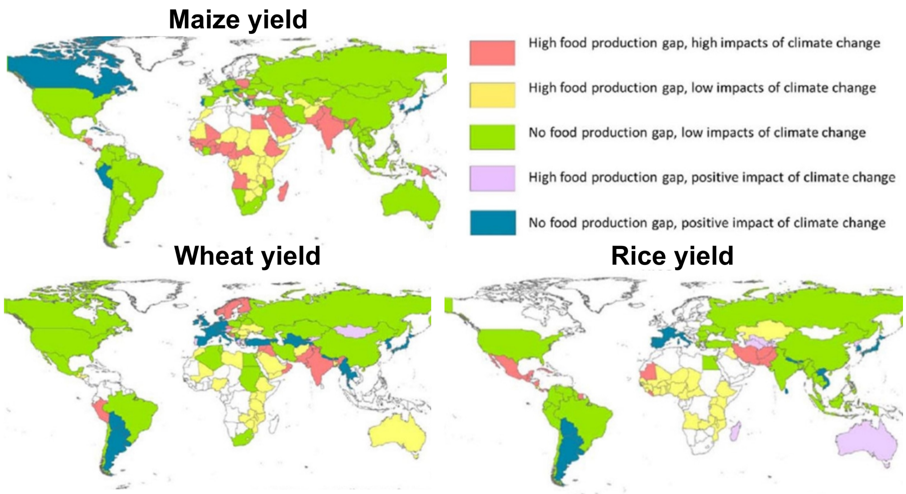


Figure D.4: Hotspots of climate change based on assessments of impacts after adaptation on crop yield at country scale for the 2050s and the production gap. Adjusted from Loboguerrero et al. (2019).

## II Climate indexes

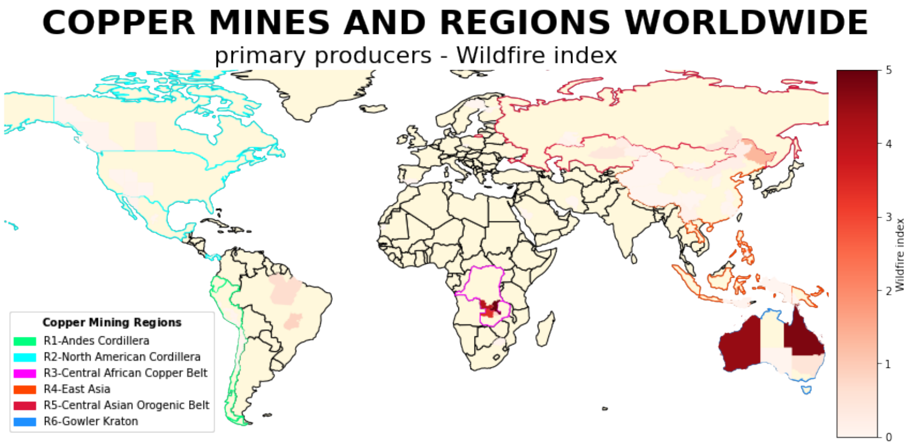


Figure D.5: Wildfires index across the globe copper mining regions. Own elaboration.

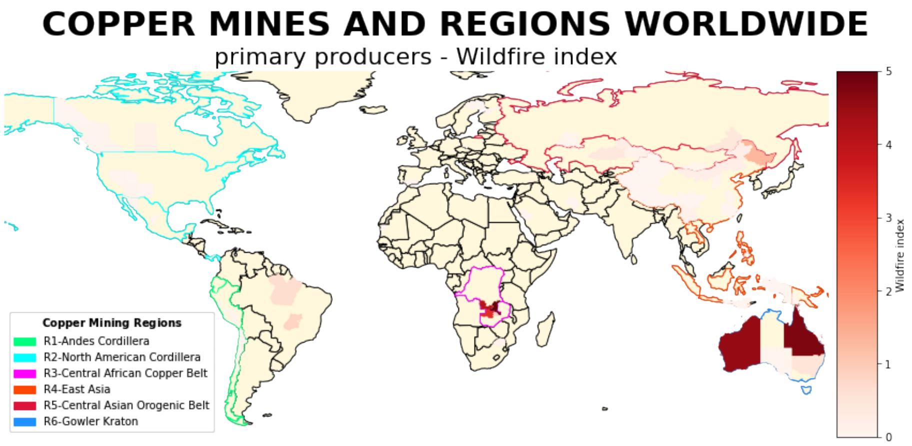


Figure D.6: Flood index across the globe copper mining regions. Own elaboration.

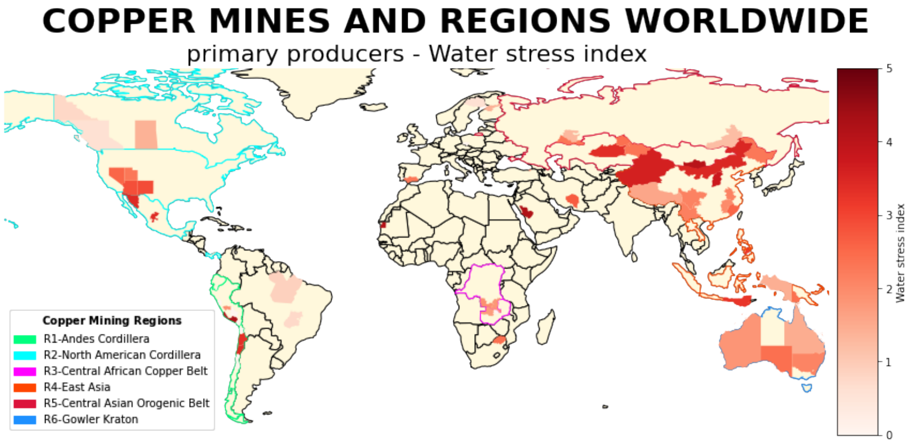


Figure D.7: Water stress index across the globe copper mining regions. Own elaboration.

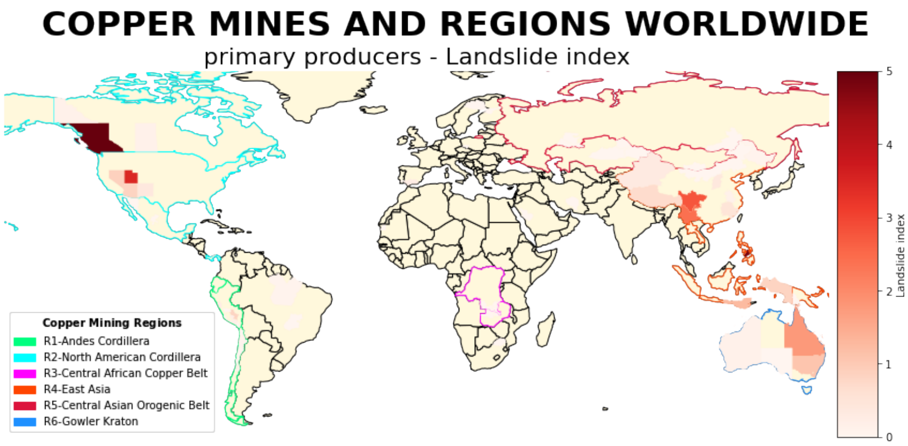


Figure D.8: Landslides index across the globe copper mining regions. Own elaboration.

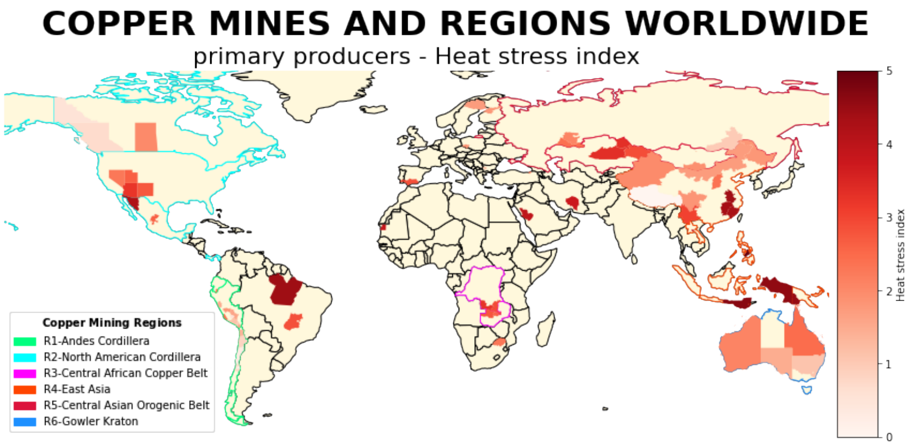


Figure D.9: Heat stress index across the globe copper mining regions. Own elaboration.

## III Case Studies

### Case studies - Region I

Andes Cordillera present notorious clustered patterns in its physical risks as the slope as bigger changes can be seen mostly at the end of the curve (see Figure D.10). This analysis allows the case studies to be focused in major risks and disregard the ones that may be irrelevant. For this particular region flooding and heat stress suggest to be the relevant physical risks, however water stress is the the highest risk of all, and it is the most stressed regions among all the studied mining regions.

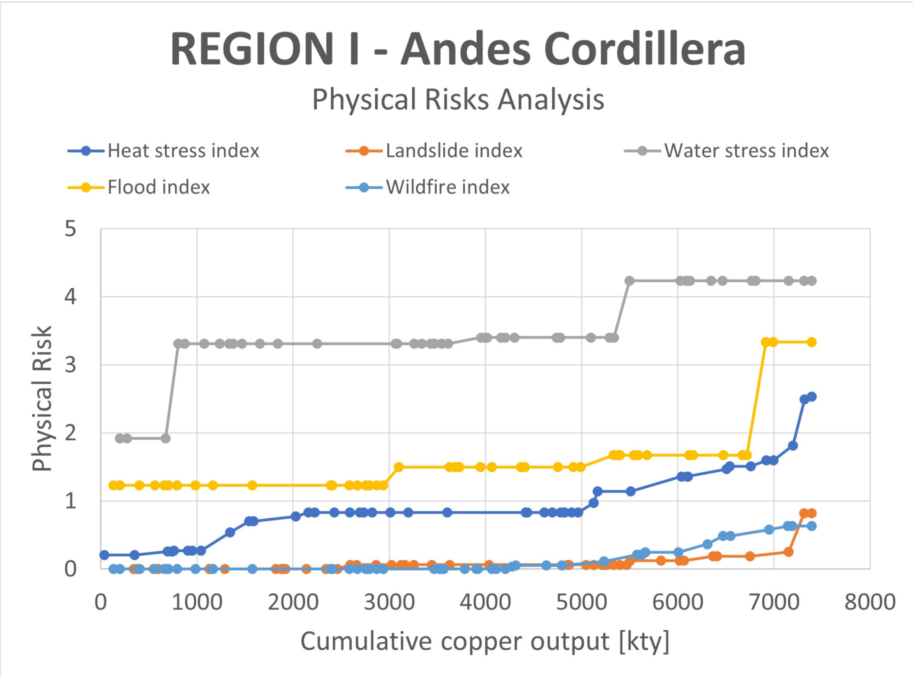


Figure D.10: Region 1 - Andes Cordillera physical risks composition. Own elaboration.

#### Case I.1: Water stress in Pelambres

Los Pelambres, located 240 kilometers north-east of Santiago in Chile's Coquimbo area, is one of the company's activities hit by the drought. Rainfall in the country's central area, where the majority of people reside and main copper mines are located, has declined by over 30% in the previous 20 years. This situation has forced Antofagasta Minerals to announce during 2021 that a lack of water in the region had impacted their flagship mine to reduce its copper output forecast for the year. The miner now projects to produce between 710,000 and 740,000 tonnes of copper this year, below than 730,000 to 760,000 tonnes previously predicted. The construction of a desalination plant at the mine, which is scheduled to commence operations in the second half of 2022, might also be impacted, according to the business, which added that a delay would jeopardize

50,000 tonnes of copper output (Jamasmie, 2021).

**Case I.2: Flooding in North Chile**

The north of Chile suffered heavy rains during 2011 that forced operations in Chile's Escondida, the world's largest copper mine, as well as Radomiro Tomic, and Chuquicamata to shut down due to safety and technical issues. secretary of the Escondida's workers union mentioned "Heavy rains and hail led to the evacuation of all workers from the jobs, which means that all operations in Escondida will be suspended until the weather conditions improve". The dis-gradually returning to normal over the weekend after a bad weather front forced management to evacuate all workers and close down the mine and processing facilities, the local press reported. Conditions continued to improve over the following days, after the cold front moved to Argentina, according to weather reports. The shut down lasted for approximately 1 day for all these mines (BNAmericas, 2011).

**Case I.3: Flooding in North Chile**

The Chilean Meteorological Authority announced heavy rains in the Antofagasta region, which led to the declaration of a red alert in the area, which was lowered the following day. This forced the main copper mines operating in northern Chile, including the most productive in the world, the Escondida mining company, and four state-owned copper deposits, Codelco, suspended their operations during 2017 due to a rainy and snow storm in the area. Codelco, the world's largest copper producer, mentioned that "due to the frontal system in the area, the divisions of the Northern District decided to implement a series of preventive measures, with the aim of safeguarding the safety of their workers, their own and contractors". This disruption affected the operations of the Chuquicamata, Radomiro Tomic and Ministro Hales, which nevertheless kept their plants operational, according to the company. El Salvador mine also shut down operations at the mine, its plant, smelter and refinery. Gabriela Mistral continued to operate although with security restrictions by protocol, according to the company. Meanwhile, the Escondida mine, controlled by Anglo-Australian BHP Billiton and which produces 5% of the world's copper, paralyzed operations as well Swissinfo (2017).

**Case I.4: Water stress in Cerro Colorado**
At the end of 2021, Chile's Environmental Court enforced a prohibition to the extraction of water from the Lagunillas aquifer in the Cerro Colorado mining site. Previously, BHP had obtained a precautionary measure limiting water extraction to only 54 l/s; that is, half of what it normally extracted for the mining operation at Cerro Colorado. After the latter decree, this action was suspended for a period of 90 calendar days; or until the mining company could prove that there was no risk of harm or uncertainty in carrying out this activity. However, the Court explained that the background information submitted by BHP does not support a different environmental status from the Lagunillas system; therefore, it found no reason to modify the precautionary measure or the application of a less intense intervention Camiper (2022).

**Case I.5: Storms in El Teniente**

Codelco Chile reported in 2016 that El Teniente Division had to suspend its production in its mine and plant processes, due to damage to the access infrastructure of personnel and supplies, as well as the interruption of the transportation system of ore to plants, product of the bad weather front affecting the O'Higgins region. The restoration of basic services and systems to restart production lasted at least three days, equivalent to a production of 5,000 tonnes of fine copper. The severe weather event, which occurred in the mountainous area where the deposit is located with rainfall of 180 mm in 48 hours, caused damage to the transport infrastructure for people and ore due to the occurrence of alluvium and overflowing of watercourses over the infrastructure. There was no damage to dams and reservoirs (Codelco, 2016).

**Case I.6: Waterstress and desalination Minajusta**

Mina Justa is located in the coastal desert, 35 kilometres from San Juan de Marcona and 13 kilometres from the Panamericana Sur highway. The region of the south coast is exposed to high risk water stress, due to the lack of water resources in the area. However, Mina Justa is close has invested around US$100 million in the construction of a terminal where it will unload chemical inputs but from which it will also extract seawater, at a rate of 900 m3/hour. The miner mentioned: "We receive the seawater and distribute it to both the oxide plant and the sulphide plant", "The use of seawater is a competitive advantage because it is abundant and available". Moreover, Minajusta will be the second mining operation in Peru to use seawater for mining processes (Energiminas, 2020).

**Case I.7: Flooding Toquepala and Cuajone**

Southern Copper's operations in Peru were paralysed for three days in 2019 after heavy rains. Southern Copper, controlled by Grupo Mexico, said in a statement on Sunday that it had paralysed on Friday its concentrator plant in Cuajone, located in the Moquegua region, affected by rains and flooding. A spokesman for the mining company said it had also suspended operations at Toquepala and Ilo as a precaution. Southern Copper carried out repairs to its railway tracks and reinforced the company's tailings tunnels to have full operation at the Toquepala and Cuajone concentrator plants. The mining firm later said operations at its Cuajone and Toquepala mines were at 100 percent on Tuesday (Reuters, 2019).

**Case I.8: Flooding Antamina**
The Antamina Copper Mine in Peru was shut down for three days in 2006 due to heavy rains and flooding, and 300 locals who had been moved to the workers' camp were allowed to return to their homes. The company released a statement afterwards "Antamina last week closed its concentrator plant to prevent flooding from higher than usual water flow rates" GM (2006).

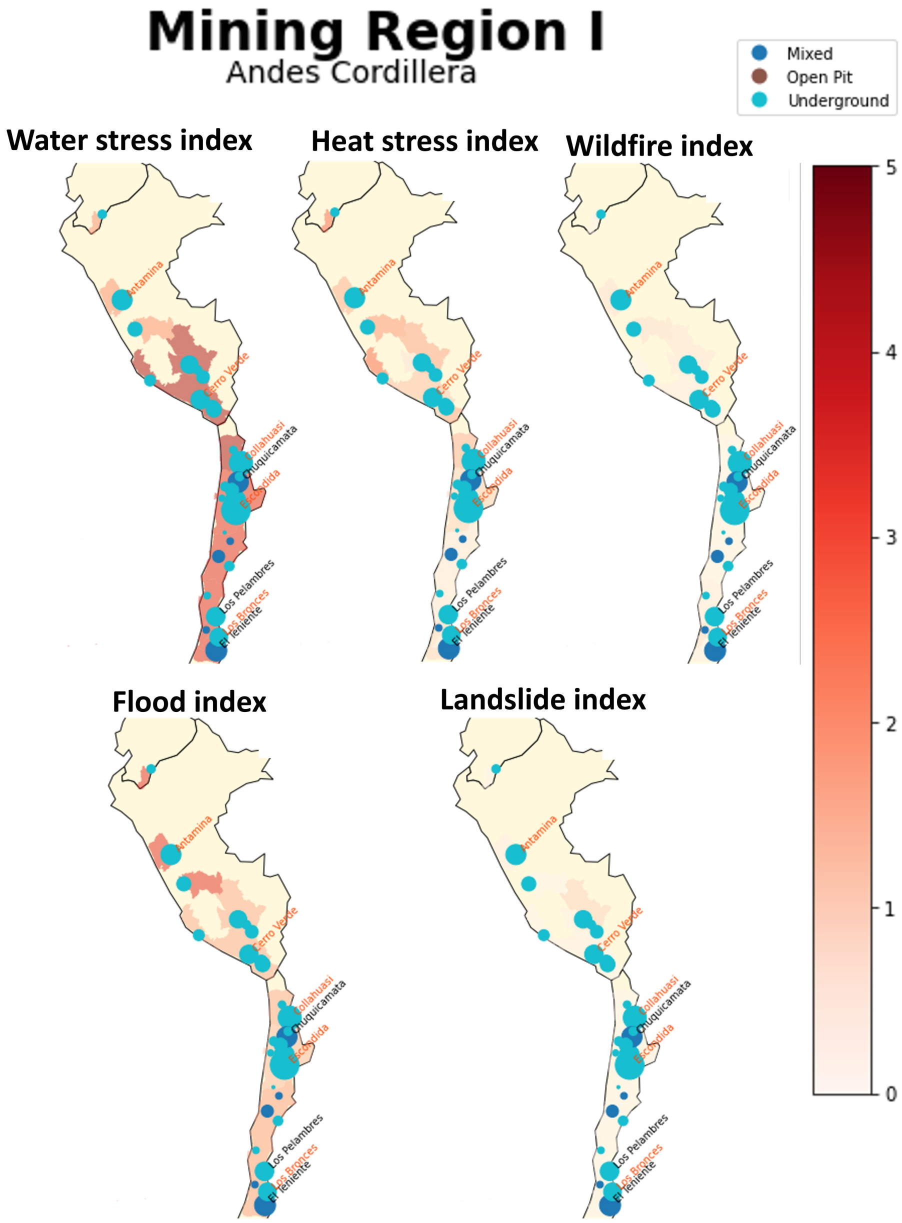


Figure D.11: Overview of physical risks in Andes Cordillera mining region. Own elaboration.

#### Case studies - Region II

As Figure D.10 shows, the American Cordillera region is quite exposed to all the studied physical risks, but mainly heat, water stress and landslides. However, based on the research performed during the case studies, wildfires stand out as one of the major causes of operational disruptions.

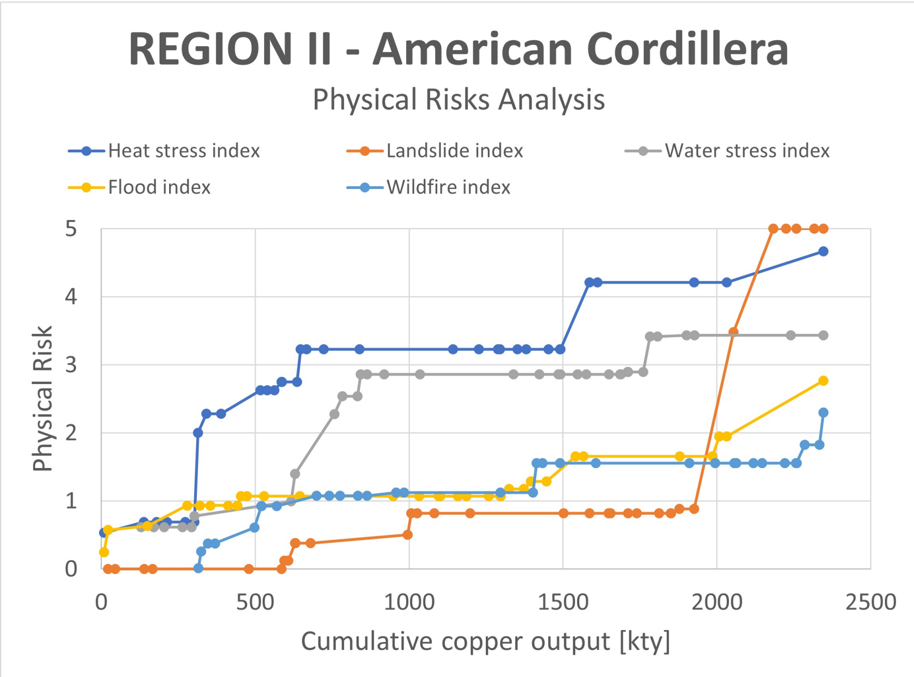


Figure D.12: Region 2 - North American Cordillera physical risks composition. Own elaboration.

##### Case II.1: Wildfires at Gilbrartar

During 2017, fast expanding wildfires in British Columbia pushed 14,000 people from their homes in the interior of the Western Canadian province, disrupting operations at two mining firms and causing damage to public utilities. Imperial Metals Corp stated that activity at its Mount Polley copper mine was "significantly reduced" as a result of some employees being evacuated from their homes, numerous roads being closed, and a nearby airport being closed. However, Taseko Mines Ltd, which has a mine close to several of the fires, claimed that although some of its employees were affected by evacuation advisories, the plant was still operating at full capacity. (Lou, 2017).

### Case II.2: Wildfires in High Valley

The Highland Valley copper mine in British Columbia, Canada, was affected by wildfire activity in 2021, forcing Teck Resources to shut down. On August 14, the district of Logan Lake issued an evacuation order, which prompted the demobilization and relocation of all on-site employees to safety. Operations resumed the day after, however Teck warned that there was still a chance that fresh wildfire smoke might cause disruptions at the oxygen plant during the fire season. The corporation stated that staff health and safety was given precedence above all other considerations while also actively monitoring the continuing wildfire danger at all operations (Skidmore, 2021).

### Case II.3: Milligan mine landslide and flooding

Heavy rain, flooding and mudslides disrupted the rail service between its Mount Milligan mine and west coast terminals in 2021. This event impacted its freight of concentrate and the delivery of some parts and consumables to the mine. Because of the severity and damages, the province declared a state of emergency that remained for several days, putting temporary restrictions such as vehicle fuel purchases and non-essential travel on severely damaged highway. This climate event did not only affected Milligan Mine, but also the surrounding ones. For instance the transport routes to New Gold's New Afton were also affected impacting sales and costs. Similarly with Teck Resources, the company said there were no impact on production at its BC operations "at this time" but there will be overall impact on Q4 due to logistics chain disruption. (MiningJournal, 2021)

### Case II.4: Community conclicts due to water stress at Buenavista

Previously, it was mentioned how water stress will undermine community problems as there will be competition over this resource with agriculture and domestic use. This particular case in Mexico provides an outlook to what water stressed mining provinces may face in the future.

During 2015, conflicts over water increased due to scarcity, pollution, intensive use of the resource in mining and agroindustry. The conflict was triggered by the non-fulfilment of the human right to water, as there is not enough water to cover the needs of the locals. As a result of this conflict, hundreds of residents of the Sonora River and miners dissatisfied with Grupo Mexico cut off the water supply to the Buenavista del Cobre mine and permanently took over the Los Patos pumping facilities adding "if there is no water for the inhabitants of the Sonora River, there is no water for Grupo Mexico". When the tap on the pumping equipment was shut off, 12,000 litres per second, which are used for the daily pumping of more than 365,000 tons of mine material for the separation of metals, ceased to be supplied (Escobar, 2015).

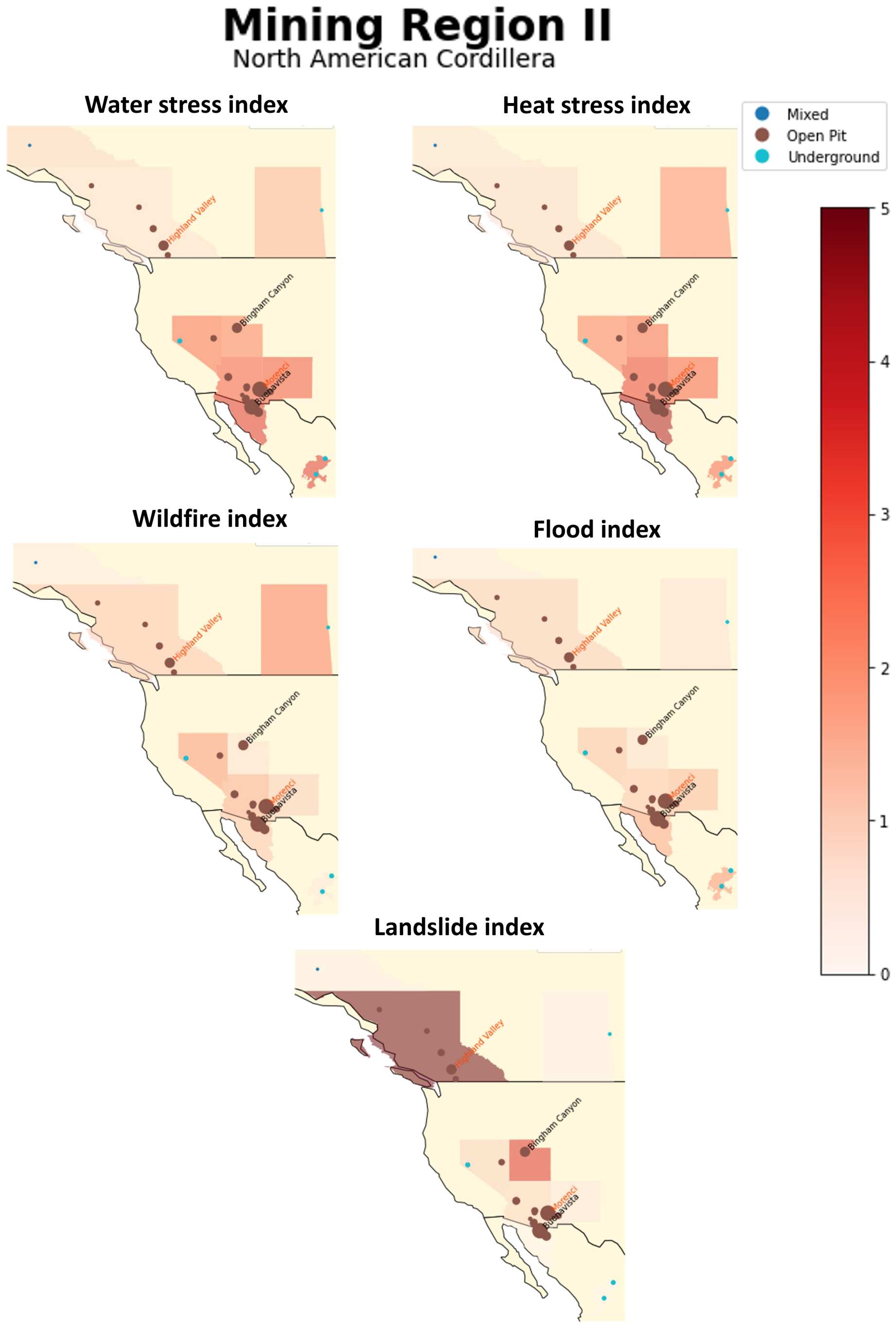


Figure D.13: Overview of physical risks in North American Cordillera mining region. Own elaboration.

**Case studies - Region III**

The African Copper Belt is mildly exposed to physical risks, where heat stress poses the major risk. Water stress is particularly low compared to the rest of the mining regions, this could be perceived as an opportunity. Even though landslides are supposed to not be a risk for this region, a fatal case was found as we will see next, however is the only event recorded for which it will be treated as an outlier for further analysis.

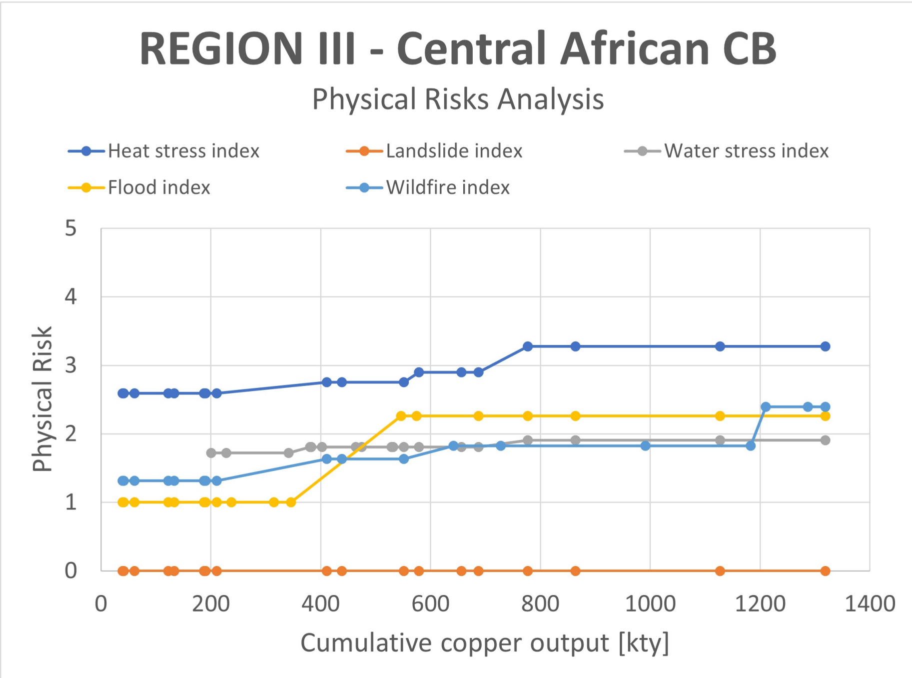


Figure D.14: Region 3 - Central African Copper Belt physical risks composition. Own elaboration.

**Case III.1: Floods disrupt production at Kwale titanium mines**

In 2022, floodings disrupted mining activities at titanium in Kwale County. Its Australian-based parent firm Base Resources announced "This series of rainstorms over recent days resulted in flash flooding that overwhelmed the dewatering systems for the three operating hydraulic mining units (HMUs),", "Recovery work is underway, with one of three HMUs back in operation and delivering approximately 45 percent of normal mining volumes." The mine resumed a week after it shut operations (Ngugi, 2022).

### Case III.2: Heatstress in Mufulira Mine Site

This case examines the entire assessment of how heat stress is influencing the productivity of future workers in Mufulira mines. The temperature data from the multiple levels at depths, all of which exceeded the occupation exposure levels of 31 degrees, were examined in the research as evidence of the negative heat conditions. However, certain preventative measures have been adopted, such as installing fans and having the People in Charge evaluate the working environment before each workday. In the study's conclusion, it was recommended that management give workers enough breaks and water to replenish what they lose via sweating. Additionally, it was recommended to management that they make sure their staff is properly trained and educated on concerns related to heat stress. Although these necessary steps will definitely have an impact on worker productivity, they are essential to maintain minimal health and safety requirements. Last but not least, it was calculated that Mopani Copper Mines would need to spend £32,550,000 on a strategy that would be implemented over the course of a year in order to adequately regulate heat at deeps section (Malambo, 2014).

### Case III.3: Flooding in Mufulira Mine Site

Flooding in Mufulira Copper Mine caused it to suspend underground copper operations in 2007. Because of its location in an area with above-average annual rainfall, Mufulira Mine frequently experiences flooding whenever there is a period of high precipitation. This disruption forced the mine to cease operations on two levels, according to Dyford Muulwa, the district commissioner for Mufulira. After floodwaters surged across two distinct levels of the underground operation, Muulwa reported that the management of the Mufulira mine halted partial mining operations at the unit of Mopani Copper Mines (MCM). He added "I received a report that there is flooding at 1,357 metre level and 1,540 metre level at the Mufulira mine which forced them to suspend operations and evacuate all the miners", "They have continued to pump out water although they have not conclusively determined where the water is coming from. This has affected production" (Reuters, 2007a).

### Case III.4: Landslide in Kamoto Mine

An unprecedented event occurred in the open pit Kamoto Copper mine in the Democratic Republic of the Congo, when a landslide resulted in 19 fatalities. A moist tropical climate predominate in Lualaba Province, with two yearly maxima in November and an average annual rainfall of over 1100 mm. According to reports, all personnel involved were engaged in dewatering activities at the time the tragedy took place (extracting liquids from the soil to lower the water table before excavation work). Around 90% of landslides happen after flooding, torrential rain, or other extreme weather events because excess pore water pressure may overcome cohesiveness in soil and sediments, causing them to flow like liquids. (Bauwens, 2016).

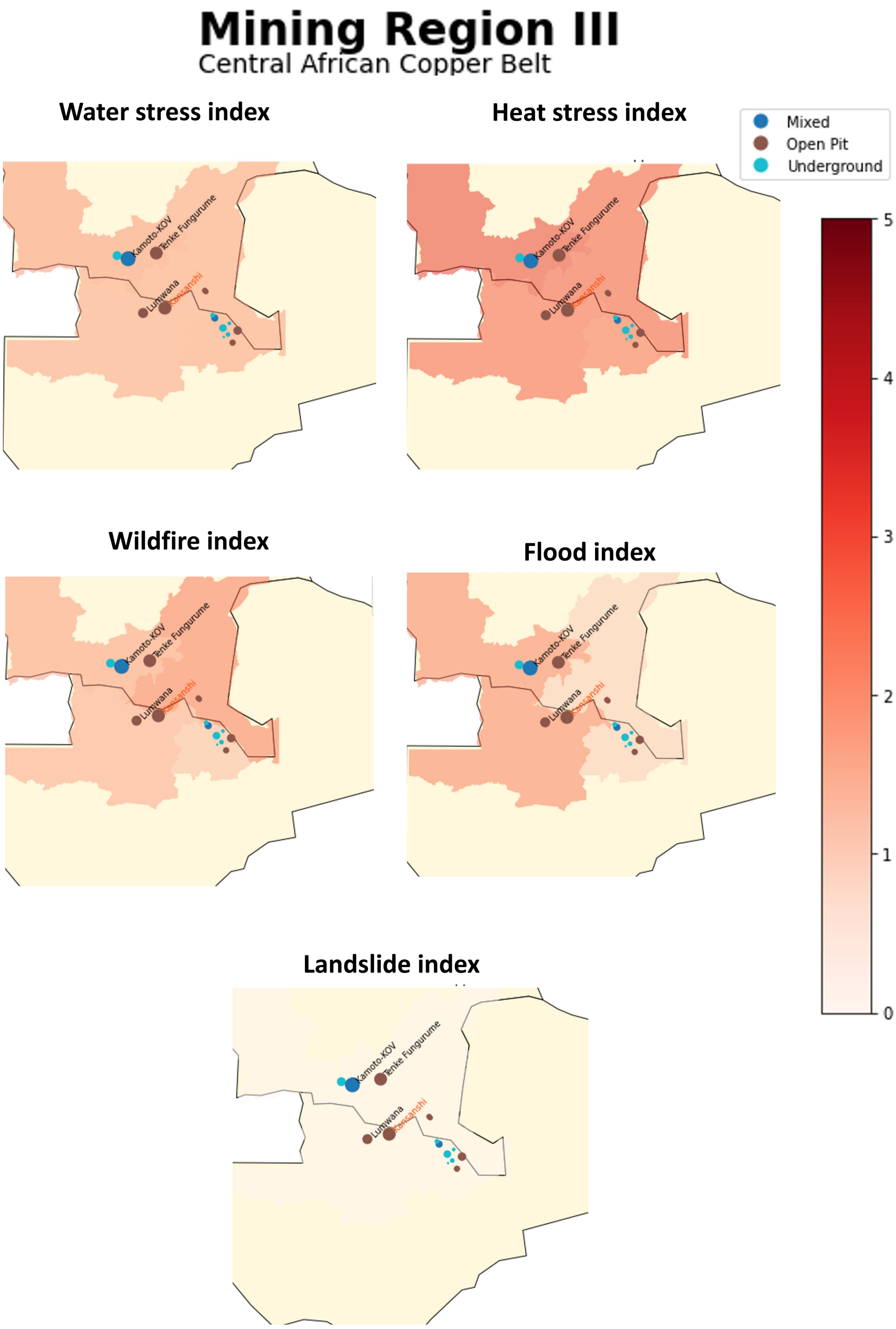


Figure D.15: Overview of physical risks in Central African Copper Belt mining region. Own elaboration.

### Case studies - Region IV

East Asian region is among the 6 regions the one most exposed to physical risks as Figure D.16 displays. Heat poses a notoriously consistent high risk as Figure D.17 shows, yet no disruption related to this risk was found, however that does not meant it will not happen under more extreme weather conditions as it poses a serious threat for workers' health.

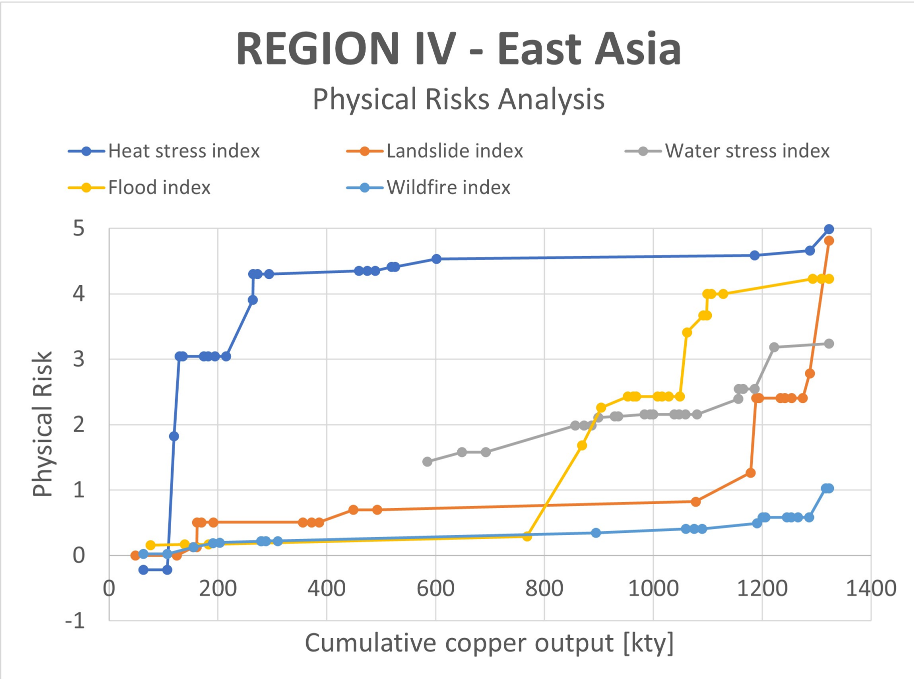


Figure D.16: Region 4 - East Asia physical risks composition. Own elaboration.

#### Case IV.1: Water stress at Ok Tedi

High water stress levels near the Ok Tedi mine has made its output to stall due to low river water in 2015. The company said in a statement. "River traffic on the Fly River into and out Ok Tedi's main river port at Kiunga has been unreliable for some weeks due to low water levels". This has affected the transport of copper concentrate product to Port Moresby for on-shipment and created uncertainty with regard to cash inflows necessary to sustain operation. The company added that the low river flow also affected operation of the Ok Menga power station, which is the main source of power for its operations (Reuters, 2015).

Later in 2022, water stress reached to a level a dispute with disgruntled landowners ended with them disconnecting water supply to PNG's Ok Tedi Mining Ltd which forced the mine to operate with its reserves for two days. The landowners claimed that the beneficiaries should be the landowners (Onepng, 2022).

### Case IV.2: Flooding and landslides in Toledo Copper Mine

By the end of 2020, a very massive landslide took place in the Carmen Copper Mine, also known as the Toledo copper mine, in Toledo City, Cebu, the Philippines, following Tropical Storm Vicky. Ten miners are confirmed to have died in this landslide. According to reports, the mine's edge has developed additional fissures, which prompted the authorities to order the evacuation of 400 households (Petley, 2020).

### Case IV.3: Landslides Grasberg

In 2019, there was a landslide at the Grasberg mine, which did not impede mining activities or result in any fatalities but did damage some of the equipment, according to authorities from the Indonesian Energy Ministry (SMM, 2019).

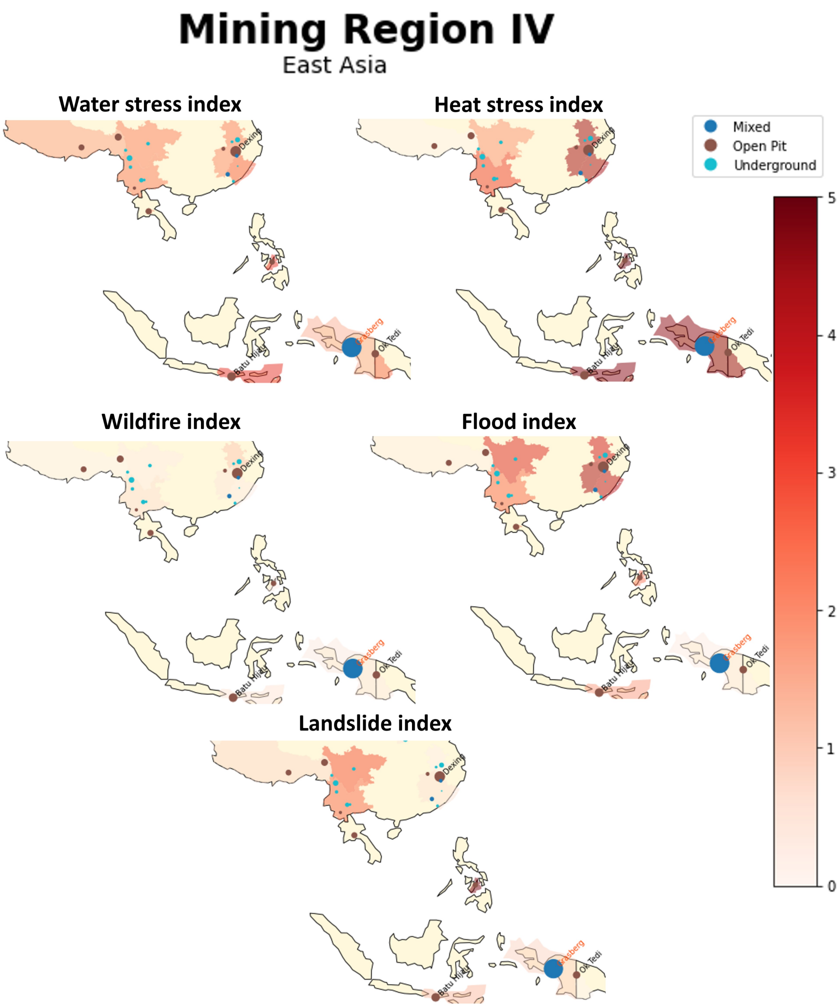


Figure D.17: Overview of physical risks in East Asia mining region. Own elaboration.

**Case studies - Region V**

Figure D.18 ranges most risks - except for landslides - from low to high physical risks, where wildfires can be exceptionally high. Heat and water stress are however consistently physical risks for this region.

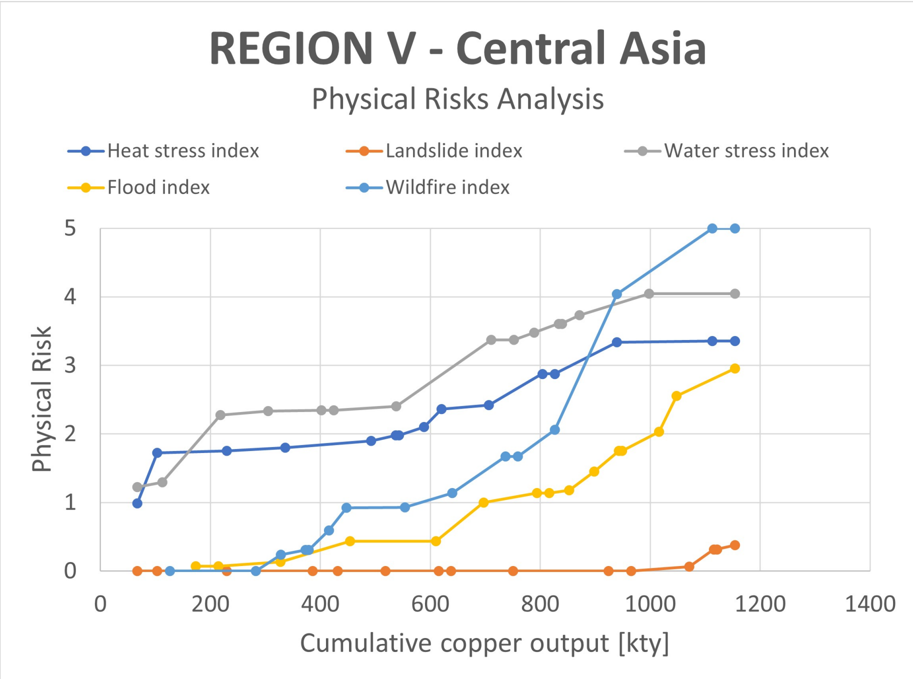


Figure D.18: Region 5 - Central Asia physical risks composition. Own elaboration.

### Case V.1: Water stress in Oyu Tolgoi

In this case there are no disruptions reported, but rather we will review the water stress related issues that have been affecting Oyu Tolgoi in recent years and how the mine has been engaging this problem.

More than 80% of Mongolia's land area is exposed to climatic extremes, making it a climate hotspot. The nature of the interaction between the mining sector and agricultural, isolated villages is also of significant importance to the people who live there, as the existence of many pastoralist communities depends on both the quantity and quality of water. There is a serious chance that mineral development may worsen the status with respect to Mongolia's already degraded water supplies because of a developing, water-intensive mining sector at a time when the nation is seeing less rainfall (Ruttinger and Sharma, 2016).

Desalination may be a solution for the central Asian nation's high seasonal runoff, local water stress, and ongoing deficits. However, it's unclear if landlocked Mongolia has the financial resources or even the right hydrological conditions to make it happen. Currently, it is up to mining corporations to ensure that their operations are as water-efficient as possible. In fact, Oyu Tolgoi is hailed as the industry standard. Over two-thirds (70%) of the mine's water consumption is recovered, recycled, and then reused. The mine obtains all of its water from an underground aquifer that is situated roughly 400m beneath the desert's surface. The majority of water savings at the mine, which has a zero-water discharge policy, are also attributed to high efficiency tailings thickeners and reclamation operations. However, local worries over Rio Tinto's mine also highlight an additional alarm about the effects of mining extraction on agriculture. They risk losing their livelihoods if mining uses water that is already in short supply. The production of irrigated food crops is also threatened by water shortages; this issue is particularly acute in the Central Zone, which supplies Ulan Bator with a large portion of its food supply (Balch, 2014).

#### Case V.2: Flooding in Zhezkazgan mine

In 2007 a flood disrupted transportation of extracted ore from the mines Kazakh copper miner Kazakhmys KAZ. However this had a small impact on the mines operations. In fact the company announced “The mine is ramping up and should be back to full output by the end of the year, slightly ahead of expectations”. This nevertheless affected momentarily the company's shares as they were down nearly 3 percent during the day (Reuters, 2007b).

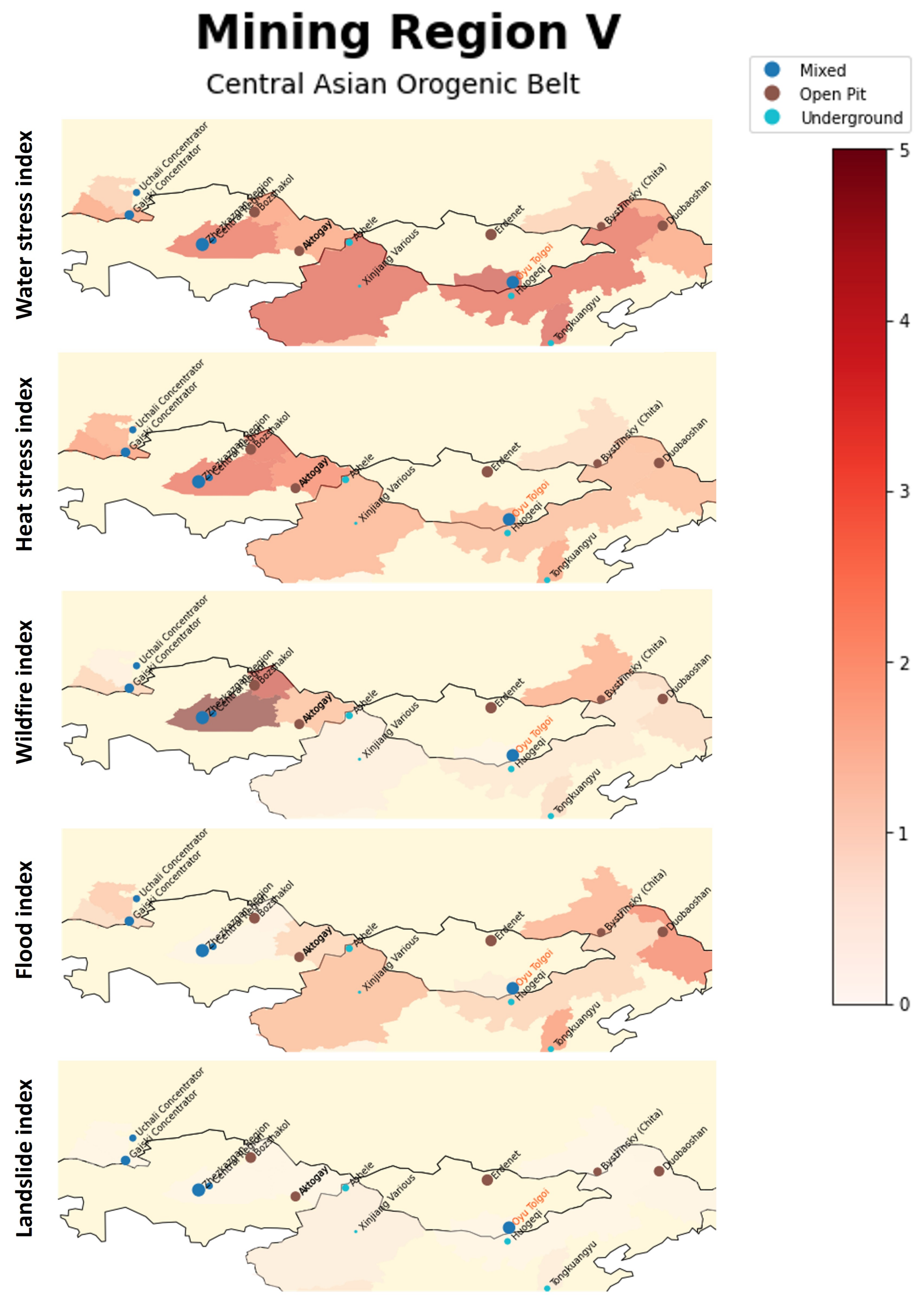


Figure D.19: Overview of physical risks in Central Asian Orogenic Belt mining region. Own elaboration.

**Case studies - Region VI**

The last region is the Gawler Craton - mostly covered in Australia - and show a very water and heat stressed area with surprisingly very high wildfire risks. Landslides here are a minor risk. This region is also very exposed to typhoons and storms that frequently provoke floodings and disruptions in supply lines and within the mines.

Smith (2013) explains Australia has recently seen wetter weather, which is consistent of how the climate is changing as a result of human-induced climate change. The Pacific Ocean's La Niña/El Niño oscillation has a big impact on Australia's climate. Australia has drier drought conditions when El Niño is present, but La Niña is associated with greater rainfall occurrences. The alternating nature of these two cycles explains why Australia has historically been known as the "country of droughts and flooding."

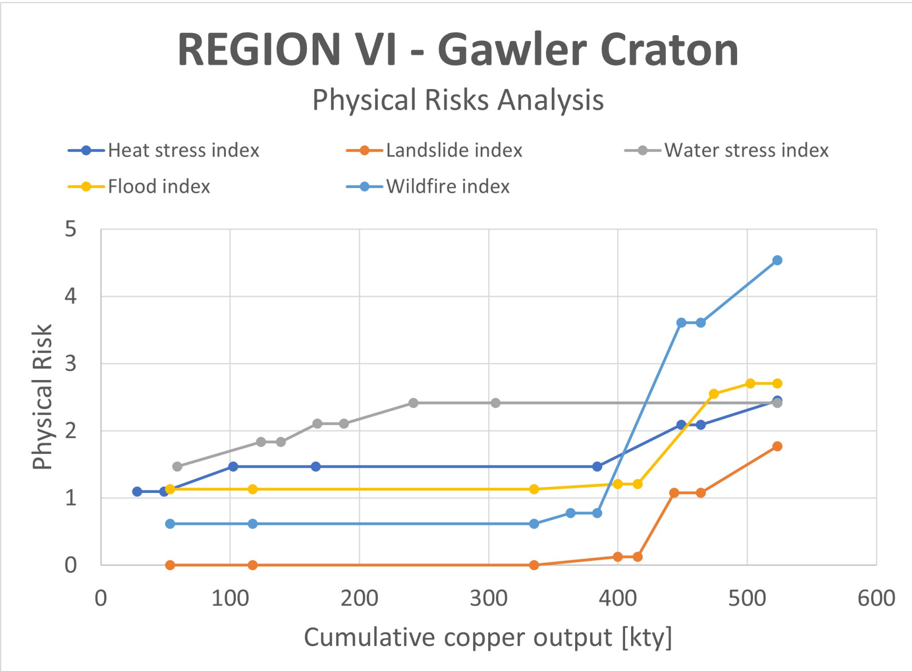


Figure D.20: Region 6 - Gawler Craton physical risks composition. Own elaboration.

**Case VI.1: Cyclone Damien disrupts DeGrussa operations**

In 2020, Tropical Cyclone Damien made landfall in the Pilbara area, shutting down the ports at Port Hedland, Dampier, and Ashburton. The DeGrussa copper-gold mine in Western Australia was partially inundated by strong rains, the firm was forced to temporarily halt operations at the mine. A light vehicle, one piece of underground mining equipment, and one portion of the decline road surface surface were the only things that were damaged since the mine quickly separated the affected region. Mining operations restarted after a site inspection by the Western Australian Department of Mines, Industry Regulation and

Safety (DMIRS) was approved. The storm had no effect on the DeGrussa concentrator, which was still processing run-of-mine stocks from DeGrussa and the neighboring Monty mine (Haselgrove, 2020).

**Case VI.2: Rain and Covid dull Oz Minerals' shine**

Wet weather conditions and Covid-19 outages caused a decline in Oz Minerals' first-quarter production in 2022. A rainfall storm in January had an impact on South Australian assets, resulting in the closure of roads and railroads and a subsequent interruption of supplies. Prominent Hill was particularly affected, with no site access through road for close to three days and restricted access for 12 days. According to he source, gold output plummeted by around 20% and copper production decreased by over 10% in the three months leading up to March. Additionally, C1 cash costs climbed from 90.9c/lb to 118.1c/lb, while all-in sustaining costs for the quarter increased from 159.6c/lb to 174.4c/lb (Iannucci, 2022).

**Case VI.3: Wildfire disruption in West Australia**

After an out-of-control wildfire in the area disrupted power supply in 2015, Newmont Mining reported that gold and copper production at its Boddington mine in Western Australia state has restarted. After many days of interruptions, NEM reports that power supply to the Boddington plant has been restored, and the processing mills are presently running at 90% of their rated capacity (Surran, 2015).

**Case VI.4: Heat stroke at Rio Tinto ended with a fatality and a fine**

By the end of 2021, Rio Tinto Exploration Pty Ltd filed a plea of guilty in the Perth Magistrates Court for failure to defend workers' safety. After three employees were subjected to harsh circumstances without the required training, the corporation was fined \$80,000 and told to pay \$7,000 in penalties. While at Mount Windell in the Pilbara area of Western Australia in 2017, two employees and a supervisor were searching for potential drill sites in rough terrain. However, the task was done in two days at temperatures that were thought to be over 37°C. In challenging circumstances, the three guys were expected to trek more than 16 kilometers each day while toting supplies and equipment. The three employees who were conducting the survey were unaware that they had to conduct heat stress assessments in accordance with Rio Tinto's policies regarding the dangers of being exposed to extreme weather, including hydration monitoring, heat stress symptoms recognition, and appropriate management. After suffering of leg pains and feeling dehydrated the day before, one of the workers fainted at the conclusion of the second day and later passed away. The corporation had written policies in place, but some employees did not know or understand them, and some managers did not enforce them (DMP, 2021).

According to DMIRS Director Mines Safety Andrew Chaplyn, heat stress is a serious risk that must be handled in all mining and exploration activities because of the climatic extremes in Western Australia. Many mining operations in Western Australia are located in outlying locations where access to medical care may be difficult, which heightens the risk posed by heat stress (DMP, 2019).

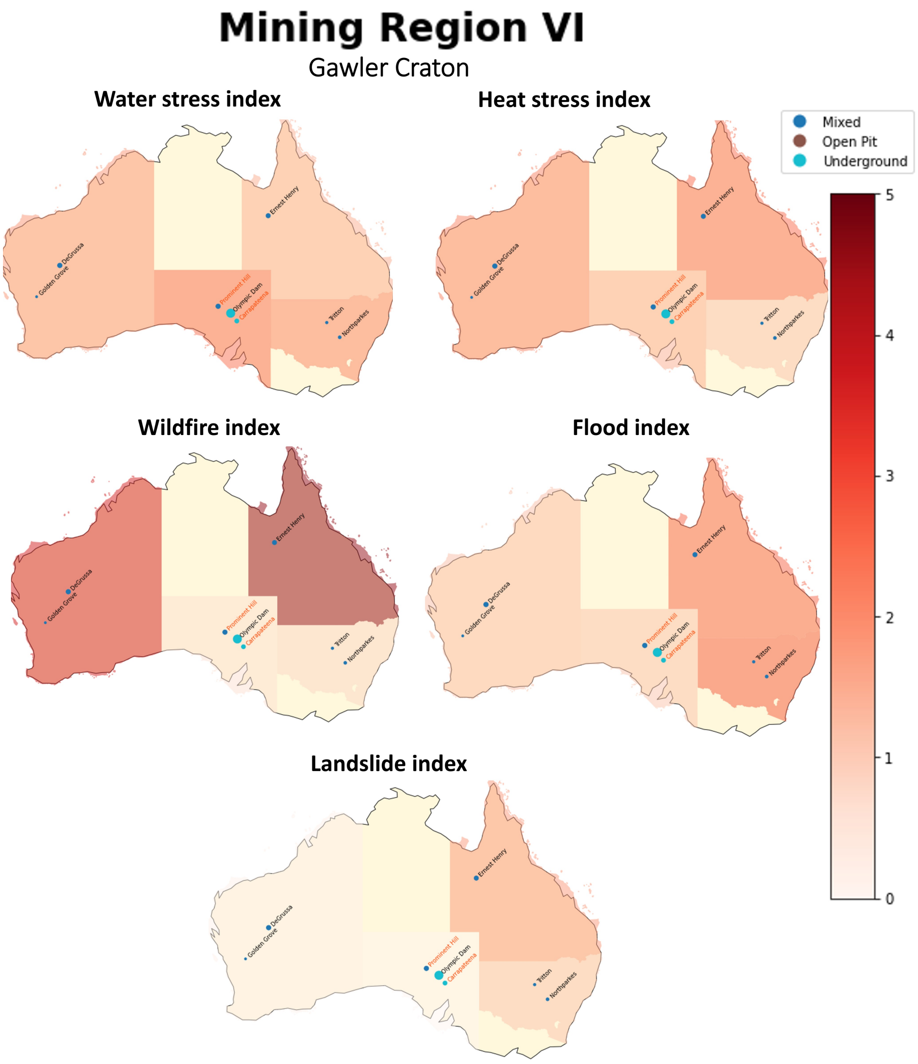


Figure D.21: Overview of physical risks in Gawler Craton mining region. Own elaboration.

# IV Results

## IV.1 Climate physical risks

Surprisingly, the physical risks become lower by 2050 (see Figure D.22). However, this can lead to wrong conclusions, since it is actually due to the fact that also mines of high physical risk have already finished their operation which makes that the curve in general has on average lower physical risks. This is verified by double-checking the physical risks with the basecase that has not been adjusted to climate scenarios.

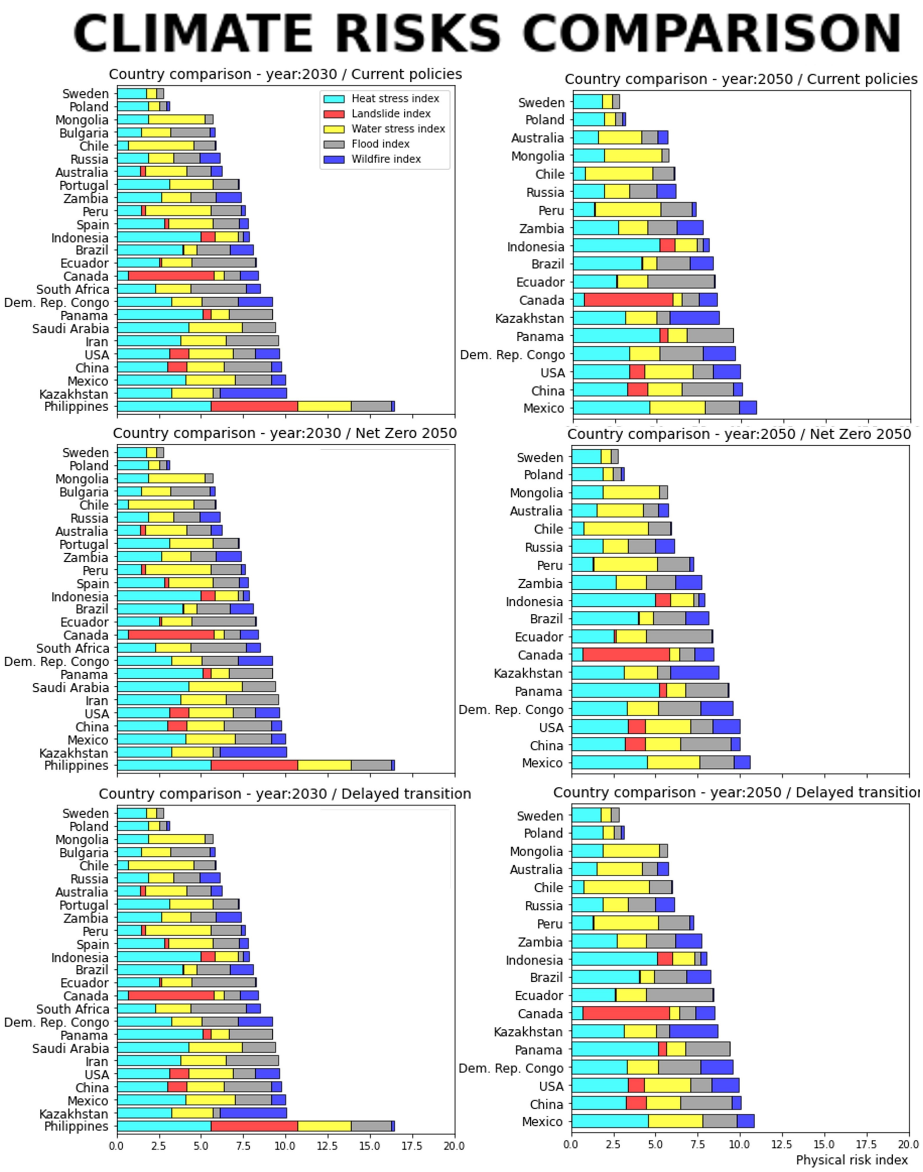


Figure D.22: Model summary. Own elaboration.