Evaluating Alternative Water Sources for Copper Processing: A Life Cycle Assessment of Seawater and Desalination in Northern Chile

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Advanced Mineral Resources Development

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ABSTRACT

Copper plays a crucial role in modern economies, especially in the ongoing energy transition, supporting various technological advancements such as renewable energy systems and electrification. Chile holds a significant position in national and global supply chains as the top copper producer in the world. Nevertheless, the nation is confronted with major obstacles in terms of extreme water scarcity, especially in areas where the majority of copper mining operations are located. This dissertation assesses the environmental impacts linked to two different water management techniques in copper processing: utilising untreated seawater and treated seawater from desalination.

To accomplish this task, a Life Cycle Assessment (LCA) was carried out using simulations from the Ecoinvent database in SimaPro software, with a specific focus on a hypothetic copper processing plant located in northern Chile. The research included an in-depth analysis of the literature to place importance on water management in mining activities and a review of current approaches for assessing environmental effects.

The findings on the comparison between the two water sources (seawater and desalinated water), reveal that the single score for seawater is more favourable than for desalinated water. The most significant impact category in both scenarios is resource use for minerals and metals. A second comparison, which excluded the copper concentration process, confirmed that seawater remained the better option, although the impact categories differed. For seawater, fossil fuel resource use became the most prominent, while for desalinated water, climate change was the key category due to its substantial contribution to greenhouse gas emissions. This study emphasises the importance of implementing new water management techniques in Chile's copper mining industry to promote sustainability, providing strategic suggestions to enhance resource efficiency and reduce environmental impacts.

Keywords: Copper, Environmental Footprint, Seawater, Desalinated water, LCA, Chile.

ZUSAMMENFASSUNG

Kupfer spielt eine entscheidende Rolle in modernen Volkswirtschaften, insbesondere im aktuellen Energiemarkt und der Energiewende, und unterstützt verschiedene technologische Fortschritte wie erneuerbare Energiesysteme und Elektrifizierung. Chile nimmt als weltweit größter Kupferproduzent eine Schlüsselposition in nationalen und globalen Lieferketten ein. Dennoch steht das Land vor großen Herausforderungen in Bezug auf extreme Wasserknappheit, insbesondere in Regionen, in denen sich der Großteil der Kupferbergbaubetriebe befindet. Diese Dissertation bewertet die Umweltauswirkungen zweier verschiedener Wasserbewirtschaftungstechniken bei der Kupferverarbeitung: der Verwendung von unbehandeltem Meerwasser und aufbereitetem Meerwasser aus der Entsalzung.

Um diese Aufgabe zu bewältigen, wurde eine umfassende Lebenszyklusanalyse (LCA) unter Verwendung von Simulationen, der Ecoinvent-Datenbank und der SimaPro-Software durchgeführt, wobei der Schwerpunkt auf einer Kupferverarbeitungsanlage im Norden Chiles lag. Die Forschung umfasste eine eingehende Analyse der Literatur, um die Bedeutung des Wassermanagements in Bergbauaktivitäten zu betonen, sowie eine Überprüfung der aktuellen Ansätze zur Bewertung von Umweltauswirkungen.

Die Ergebnisse zeigen einen Vergleich zwischen den beiden Wasserquellen (Meerwasser und entsalztes Wasser), der offenbart, dass das Einzelergebnis für Meerwasser günstiger ist als das für entsalztes Wasser. Die bedeutendste Wirkungskategorie in beiden Szenarien ist die Ressourcennutzung für Mineralien und Metalle. Ein zweiter Vergleich, der den Kupferkonzentrationsprozess ausschloss, bestätigte, dass Meerwasser weiterhin die bessere Option bleibt, obwohl sich die Wirkungskategorien unterschieden. Beim Meerwasser wurde die Ressourcennutzung fossiler Brennstoffe zur hervorstechendsten Kategorie, während beim entsalzten Wasser der Klimawandel aufgrund seines erheblichen Beitrags zu den Treibhausgasemissionen die Schlüsselrolle spielte. Darüber hinaus zeigen Sensitivitätsanalysen, dass kleine Zuwächse in der Tellurproduktion die Gesamtergebnisse erheblich beeinflussen. Diese Studie betont die Bedeutung der Implementierung neuer Wasserbewirtschaftungstechniken in der chilenischen Kupferbergbauindustrie zur Förderung der Nachhaltigkeit und liefert strategische Vorschläge zur Steigerung der Ressourceneffizienz und zur Reduzierung der Umweltauswirkungen.

Schlüsselwörter: Kupfer; Ökologischer Fußabdruck; Meerwasser; entsalztes Wasser; LCA; Chile

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AE: Accumulated Exceedance
AMD: Acid Mine Drainage
$Ca(OH)_2$: Calcium Hydroxide
$CaCO_3$: Calcium Carbonate
CaO: Calcium Oxide
$C_2H_4O_2$: Acetic Acid
Cu: Copper
DGA: Dirección General de Aguas (General Department of Water)
EF: Environmental Footprint
EU: European Union
GHG: Greenhouse Gases
GLO: Global
GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWP: Global Warming Potential
HDPE: High-Density Polyethylene
IPCC: Intergovernmental Panel on Climate Change
ISO: International Organization for Standardization
JRC: Joint Research Centre
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
MW: Molecular Weight
NaCl: Sodium Chloride
NaClO: Sodium Hypochlorite
NaOH: Sodium Hydroxide
$Na_2S_2O_5$: Sodium Meta-bisulphite
NMVOC: Non-Methane Volatile Organic Compounds
ODP: Ozone Depletion Potential
PACC-RH: Plan de Adaptación al Cambio Climático para los Recursos Hídricos
PS: Pumping Station
RO: Reverse Osmosis
S: Sulfur
SX-EW: Solvent Extraction and Electrowinning
Te: Tellurium
XRF: X-ray Fluorescence
WRI: World Resource Institute

1. Introduction

1.1 Problem Contextualization

Chile is currently the highest producer of copper (Cu), accounting for 24% of the global production of it, and it has the largest copper reserves of all countries, with 190 million metric tons guaranteeing copper production for roughly the next 100 years at the current extraction rate. The mining sector in Chile is of great significance as it contributes considerably to the economy of the country and the world in general (ITA, 2023). Given its dominant role in copper production, Chile's resources are closely tied to global supply chains, particularly in the EU, where copper is crucial for technological and energy-related industries. In 2023, the European Commission published a fifth list comprising 34 Critical Raw Materials (CRMs) (European Commission et al., 2023). Despite not meeting the CRMs thresholds, Cu was included on the CRMs list as Strategic Raw Materials (SRMs) under the CRMs Act. Copper is particularly critical for the ongoing energy transition, and it witnessed a consumption of 20Mt in 2020 for electrification across various strategic technologies (European Commission, 2023).

The choice to evaluate copper in this research is due to its role as “the most widely used mineral in clean energy technologies” (IEA, 2021). Furthermore, Chile is categorised by the World Resource Institute (WRI) as one of the extremely high water stress areas in the world (See Figure 5). Most of Chile’s copper reserves and 93% of the country’s current and planned mining projects are located in highly water-stressed regions, leading to ongoing social conflicts over water usage (WRI, 2015; Campero & Harris, 2019; Garcia-Zavala et al., 2023). In response, the Chilean mining industry has committed to sourcing most of its water from desalination plants within the next decade (Cochilco, 2018), especially considering the severe droughts affecting both public and commercial water supplies in the northern regions.

The copper industry is essential to the global decarbonisation effort. The rise of low-carbon technologies, such as wind turbines, solar panels, and electric vehicle batteries, has driven an increased demand for critical minerals like copper, neodymium, and lithium. These minerals are essential for the manufacturing and operation of these technologies, thus supporting the transition to a low-carbon economy (Moss et al., 2014). Chile, as one of the world's leading copper producers, faces a significant challenge due to its designation by the WRI as one of the most water-stressed countries in the world. The country is at risk of depleting its water resources by 2040, exacerbating the difficulty of managing water for mining operations (WRI, 2015). While there has been substantial research on the environmental impacts of copper mining, particularly regarding energy use, emissions, and resource depletion, there is a notable gap in the literature concerning the use of seawater and desalinated water as alternative water sources in copper mining operations. Previous studies have primarily focused on conventional freshwater sources and the environmental impacts associated with these. Although some research has begun to explore the potential of seawater and desalination in mining, these studies often lack a comprehensive life cycle perspective and do not fully address the comparative environmental performance of these water sources.

This dissertation assesses two different water management strategies as traditional continental water sources are no longer suitable for mining in northern Chile because of severe water shortages. More specifically, it examines seawater and desalinated water, two water sources that are becoming more and more important in the copper mining industry. Desalination is becoming increasingly significant as a viable answer to water scarcity. However, its environmental effects are still not well defined. By comparing the Life Cycle Assessment (LCA) of the two water sources in copper beneficiation, this study emphasises the significance of these methods and provides a detailed environmental evaluation to guide sustainable mining practices. The LCA method enables a comprehensive grasp of the effects across the entire life cycle, from resource extraction to disposal, playing a crucial role in tackling resource and environmental issues.

1.2 Master Dissertation's Objectives

The aim of this dissertation is to determine the most sustainable and efficient water management techniques for copper processing facilities in northern Chile, considering raw seawater versus desalinated seawater in copper processing, and provide recommendations on how to improve the sustainability of this system.

This study seeks to advance sustainable methods in the copper mining sector, especially in areas with limited water resources. The results will allow comparison between the systems, identification of environmental hotspots, and recommendations that contribute to enhancing resource efficiency and promoting environmentally conscious practices in mining activities.

1.3 Master Dissertation's Structure

The master dissertation consists of 6 chapters to address the comparative LCAs of the two water sources used in a copper processing plant and their environmental impacts in Chile. It starts with *Chapter 1: Introduction*, it is an introductory section to present the topic by giving the problem contextualization and the objectives of the master dissertation.

Then, *Chapter 2: Copper Global Market and Context in Chile* covers the copper industry from a global perspective and then gives the context-specific situation in Chile. This chapter also covers the water scarcity situation of Chile, the geological context and the energy transition of Chile.

Chapter 3: State of the Art reviews the state of the art of the LCA. It begins with a literature review of LCA methodology, the description of the concept, and all the methodology behind this analysis, followed by a section on LCAs in copper mining. Finally, a section focused on water use in copper mining highlights the need for a more inclusive analysis within the industry and the current recommendations to tackle the challenges related to water use.

Chapter 4: Methodology outlines the approach used to conduct a comparative LCA of two water management scenarios in copper processing in Chile: scenario 1) using raw seawater and scenario 2) desalinated seawater. The chapter begins with a detailed description of the case study and scenarios, followed by the application of the LCA methodology using SimaPro software in accordance with ISO 14040. It includes a definition of the goal and the scope, followed by an inventory analysis, an impact assessment and the final interpretation of the results.

Chapter 5, Results and Discussion, presents the environmental impacts of both scenarios. The chapter begins with a comparison of the characterised values to identify the most significant categories within the environmental footprint 3.1 methods. Next, the processes contributing to these categories are analysed, and their output substances are identified. The chapter continues with an analysis of each scenario separately identifying their impact categories, processes and output substances. This is followed by a comparative analysis that excludes the copper concentration process in order to get a clearer view of the water systems employed. The chapter concludes with a sensitivity analysis and offers recommendations for enhancing both scenarios.

The last part of this dissertation is *Chapter 6: Conclusions*, which discusses the environmental impacts of copper concentration in Chile, focusing on water resources and energy transition. It evaluates scenarios using seawater and desalinated water, emphasising the importance of LCA and renewable energy integration for sustainable copper mining operations and introduces new ideas for future studies.

2. Copper Global Market and Context in Chile

2.1 Copper Market Overview

Due to its high electrical and thermal conductivity, along with corrosion resistance and durability, copper is a highly versatile metal and is considered essential in modern society. Copper plays a critical role in the global economy due to its importance across various industries, including traditional sectors such as construction, electronics, and transportation, as well as emerging fields that support the energy transition, particularly renewable energy. The construction industry heavily relies on copper for various applications, including electrical wiring, plumbing, and numerous infrastructure projects. Meanwhile, the electrical and electronics sectors depend on copper for essential functions such as power generation and transmission, telecommunications, and the production of electronic devices (Copper Smith, 2024). Additionally, copper is highly valued in manufacturing sectors such as automotive, machinery, and appliances due to its outstanding conductivity and heat transfer capabilities. Its importance is further stressed by its prevalent use in renewable energy technologies, including wind turbines and solar panels, as well as its essential role in telecommunications and data transmission (Wang et al., 2021).

In recent years, the copper market has been experiencing significant growth. This growth is mainly driven by several factors, including rapid industrialisation and urbanisation in developing markets such as China and India, where there is a meaningful demand for copper for construction and manufacturing purposes. In addition to that, the growing worldwide dependence of battery and electric vehicle (EV) industries on substantial amounts of copper further fuels the demand (Skyquest, 2024). Moreover, in the Middle East and Africa, the copper market is also growing rapidly. In the Middle East, countries like Saudi Arabia, Iran, and Oman are heavily investing in infrastructure development, which drives copper demand, especially for electrical wiring and plumbing applications. In Africa, countries such as Zambia, the Democratic Republic of Congo, and South Africa are expanding their mining operations due to abundant copper reserves (Skyquest, 2024). These regions are also investing in renewable energy projects, such as solar and wind farms, which require significant copper wiring and components, further increasing the demand for copper. This increase in global demand translates into the expansion of the global copper market. As shown in Figure 1, the global copper market size in 2022 was approximately $304 billion, and it is projected to grow to $498 billion by 2032 (Precedence Research, 2023).

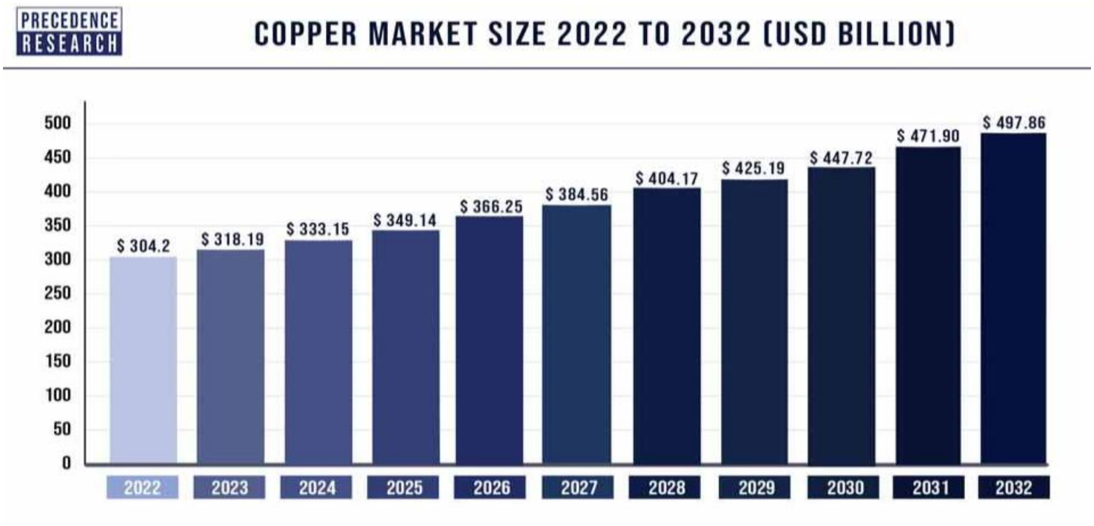

Figure 1: Global copper market size between 2022 and 2032 (Precedence Research, 2023)

Due to the increasing demand for copper and the lack of economic competition because of the uneven geographical distribution of copper around the world, the price of copper has risen remarkably in the past years. As shown in Figure 2, over the last four years, the price of copper has increased from $5,000 per ton to the current price of June 2024 of $10,040 per ton (LME, 2024). Copper has doubled its price since 2020 and has become a crucial metal in the global industry, directly affecting global stability (Liu et al., 2024). Even though the copper price has increased in the past years, the supply of copper is uneven due to several reasons, including geopolitical and transportation factors as well as different other technological and labour resources of the exporting countries. In the current complex international situation, these trade behaviours, which are not driven by profit maximisation, will continue to motivate the fluctuations of copper even further (Li et al., 2023). Consequently, the fluctuating copper prices will influence the national economic development of different countries, as copper is an important resource linked to economic development (Namahoro et al., 2022).

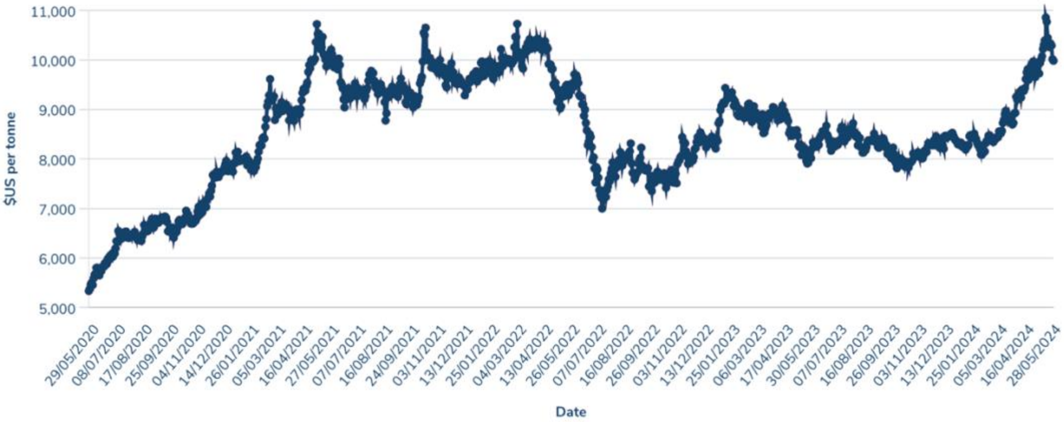

Figure 2: Graph of the copper price over the last four years (LME, 2024).

According to GlobalData's mines and projects database, in 2022, there were more than 709 copper mines in operating globally, of which 67 are in Chile, (GlobalData, 2022). As stated before, Chile is one of the leading copper producers in the world, among all the mines, Escondida is acknowledged as the largest copper mine globally in terms of capacity, with an annual production of approximately 1.4 million tons. Maintaining its dominance in the global copper market, Chile contributes over 30% to the total global supply and accounts for one-third of the global copper production. In 2020, Chile achieved a copper production of 5.73 million tons, with copper exports amounting to $15.7 billion. Chile's dominance in the market is reinforced by its extensive copper reserves, advanced mining technology, and favourable geological conditions. This robust production capacity ensures that Chile remains a principal contributor in meeting the increasing global demand for copper (Abbas et al., 2023).

In 2022, copper exports were valued to contribute to more than 13% of the country's GDP and represent about 58% of the country's total exports. Primary export markets for Chilean copper include China, Japan, and the European Union (ITA, 2023). Despite facing challenges such as fluctuating global prices and environmental concerns, Chile continues to lead in copper production, with companies investing in sustainable and innovative mining practices. In the Chilean copper mining sector, 72% of mines are privately owned and operated by mining companies, with the remainder being under state ownership and operated by Codelco a state-owned enterprise. Furthermore, the market also includes the participation of companies from Canada, Australia, Europe, and Asia (ITA, 2023).

Future copper supply scenarios present different viewpoints, highlighting the need for strategic anticipation and proactive measures to navigate potential resource constraints. For instance, in a study by Sverdrup et al. (2017), an integrated model was utilised to assess future metal supply. Their findings suggest that demand for key metals like copper, zinc, and nickel, which are crucial for the low-carbon transition, is projected to peak within the next 40 years. On the contrary, Rötzer & Schmidt (2018) offer a more optimistic perspective on mineral reserves, asserting that declining ore grades, typically perceived as signs of resource exhaustion, should be interpreted within the context of increasing demand and advancements in extraction technologies. They argue that these developments imply enhanced profitability for lower-grade ores, challenging dominant narratives of forthcoming scarcity in mineral resources, this also means that lower-grade ores will require significantly higher water consumption. Mudd & Jowitt (2018) present a similar outlook for reserves, highlighting a significant growth in known mineral resources. They emphasise that the availability of resources is principally governed by social, environmental, and economic factors, rather than geological or physical depletion. They are indicating that the understanding of mineral reserves can expand, and this is not solely limited by the physical amount of minerals in the ground but also by the extent of the increasing exploration efforts and technological capabilities. This perspective offers a counterpoint to the prevailing discourse on mineral resource scarcity, suggesting a more resilient outlook for future supply.

In conclusion, the copper market is crucial for worldwide industries, particularly in areas driving the shift towards renewable energy and cutting-edge technologies. The rising need for copper is driven by industrialization in developing nations, growing electrification, and the emergence of renewable energy technologies. Nevertheless, this request also gives rise to concerns about potential limitations in supply and fluctuations in prices, which could have a major impact on worldwide economic stability. Chile's important role as the top copper producer remains essential in meeting demand, particularly as its resources become more connected to the European Union's goals for sustainable energy and vital raw materials. The availability of copper in the future will be influenced by advancements in mining technology, economic and geopolitical factors, and the global push for environmental sustainability, in addition to its geological availability.

2.2 Geological Context of Copper in Chile

Chile is located on South America's southwestern coast with a total surface area of 756.700m^2 (*World Bank Open Data*, 2016). Chile's abundance of copper deposits is attributed to its positioning within an active tectonic zone, where the Nazca Plate (ocean) is actively subducting below the Central Andes Plate (continental). This ongoing subduction process provides the necessary geological conditions conducive to the formation of copper, being the north of Chile the area with the most copper deposits of the country accounting more than 60 copper mines, see Figure 3 (Tapia et al., 2019). Different types of ore deposits can be found all over the country such as porphyry, epithermal or IOGC, being chalcopyrite the mineral that is the most common source of copper (Olavarria & Cantallopts Araya, 2016).

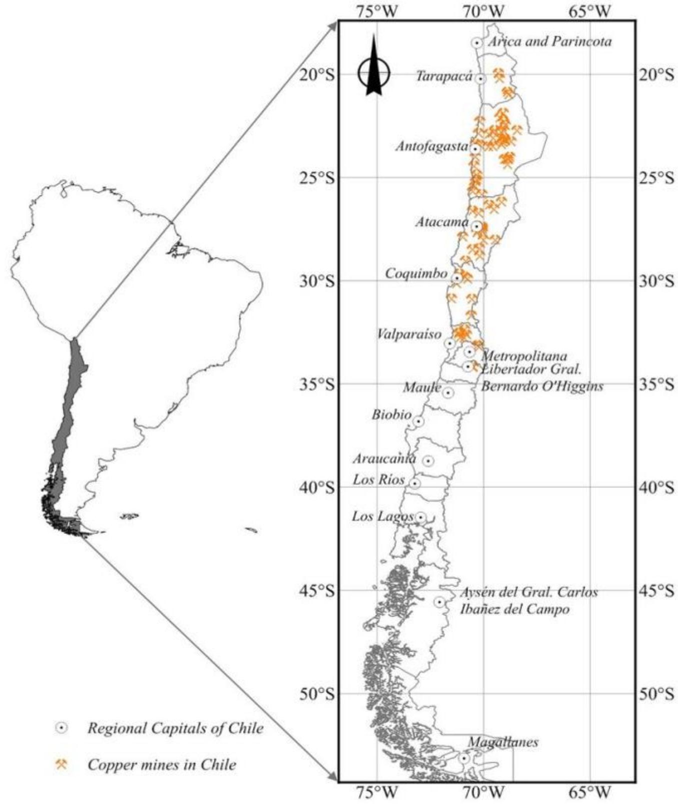

Figure 3: Map from the author Tapia et al. (2019) of the copper mines in Chile and the regional capitals of the country.

The copper deposits are mainly located within three mountain ranges, starting with the well-known Chilean Andes hosting porphyry Copper-Molybdenum (Cu-Mo) deposits of the Miocene age (Klemm et al., 2007). The second copper deposit is located at the Domeyko Cordillera which contains also porphyry Cu-Mo deposits but from a different age, Eocene-Oligocene age (R. H. Sillitoe & McKee, 1996). And the third is, as well as the Coastal Cordillera hosting iron oxide copper gold (IOCG), stratabound, and porphyry deposits of the Jurassic-Early Cretaceous age (R. Sillitoe, 2003; Trista-Aguilera et al., 2005; Vivallo & Henriquez, 1998).

2.3 Copper Supply Chain

Many authors had defined the supply chain over the past years, one of the latest definitions of supply chain was done by Pienaar & Vogt, (2009). The authors defined Supply Chain as “a general description of the process integration involving organisations to transform raw materials into finished goods and to transport them to the end-user.” The copper supply chain can be divided into 7 stages, three in the upstream and four in the downstream: upstream activities include (i) mining and extraction, (ii) crushing, grinding and concentration, and (iii) smelting, while downstream activities are (i) manufacturing and fabrication, (ii) distribution, (iii) end-use industries, and (iv) recycling (Fernandez-Stark & Bamber, 2021).

The first step of copper’s supply chain is the mining and extraction of copper deposits around the world. These copper deposits are presented in different types of deposits as previously mentioned in section *2.2 Geological context*, and most of them are located in North and South America (Berger et al., 2008; Cunningham et al., 2008). Chile stands as a dominant figure in global copper production, hosting the largest reserves worldwide with a total amount of 190,000kt of copper, followed by Australia, which holds 97,000kt. Beyond Chile and Australia, copper reserves are also notably present in Peru, Russia, Mexico, the U.S., the Democratic Republic of Congo, Poland, China, Indonesia, Kazakhstan, Zambia, and Canada (Figure 4).

This copper can be extracted from three different types of ore: sulphide, oxide or mixed ores. The sulphide ores have the highest copper concentrations but are less abundant and require more expensive techniques to extract the metal. On the contrary, oxide ores provide lower grades but are more abundant and are cheaper to mine because they are found closer to the surface. There are two main unique techniques used for copper mining, namely, open-pit mining, which is the most common technique, and underground mining (CDA, 2024). When it comes to the processing, once the ore is extracted, it needs to be refined through crushing, grinding and concentration processes. China leads the refining industry, refining 10,570kt of copper, followed by Chile with 2,239kt and Japan with 1,558kt. While other countries also contribute to refining efforts, they only provide 11,034kt in total, almost as much as China‘s output alone (Wilson Center, 2022).

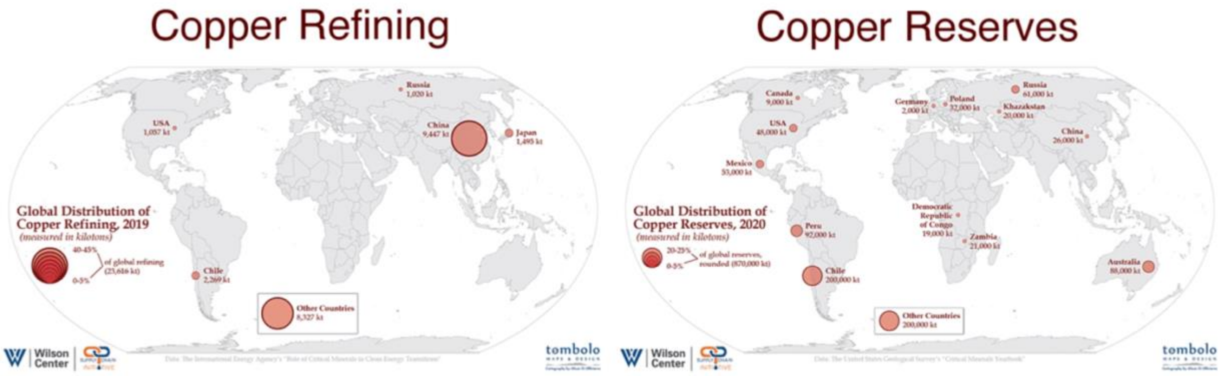

Figure 4: Global map of the copper reserves and copper processing pioneer countries (Wilson Center, 2022).

The method to concentrate copper depends primarily on the type of ore, with the mineral composition being key to choose the appropriate extraction method. On one hand, for sulphide ores froth flotation is the most common method for extracting copper. This process involves several steps: initially, the ore is crushed and ground into powder, which is later mixed with water and chemicals to create a slurry. Air bubbles are introduced into the slurry, selectively attaching to the copper sulphide minerals and separating them from the gangue. Following flotation, smelting is employed, wherein the concentrated copper sulphide minerals undergo further processing. This process involves heating them in a furnace with fluxes, such as silica and limestone, to produce molten copper matte. The matte is then refined to obtain pure copper (Wills & Finch, 2016).

On the other hand, oxide ores use leaching as a primary technique, where the ore is irrigated with a solvent, typically sulfuric acid or ammonia, to dissolve the copper minerals. The resulting copper-rich solution is collected and processed through solvent extraction and electrowinning (SX-EW) to produce copper cathodes. Additionally, heap leaching may be employed in some cases, where oxide ores are placed on a heap and irrigated with a leaching solution to extract copper. This method is suitable for low-grade ores or ore bodies that are too large to be economically processed through conventional methods. Finally, mixed ores involve a combination of the techniques mentioned above, tailored to the specific mineral composition and characteristics of the ore (Schlesinger et al., 2022). After the concentration process comes the smelting, where the concentrated material is subjected to different techniques as roasting and smelting to get a higher concentration of copper (Schlesinger et al., 2011).

Extraction, refining and smelting of copper can be explained by different trade flows. Flows of mined and refined copper, dominated by Chile, being a country that exports mined copper and refined copper. And flows of smelters led by China, which is the first importer of refined copper, and also one of the biggest copper smelters, also leading the smelters flow (Wilson Center, 2022).

The downstream activities of the copper supply chain, manufacturing and fabrication rely into companies that buy the concentrated ore, they are responsible of manufacturing and fabrication of the products.

Also, the distribution falls under the responsibility of the manufacture company or just into a service company that provides transport and logistics. Finally, the end-use industries are provided with the copper being the last step to the final costumer. The last step of the copper supply chain is recycling, consisting of reintegrating materials back into the production loop (Ellen MacArthur Foundation, 2020).

2.4 Water Scarcity in Chile

Water scarcity has become a critical matter in Chile, being ranked amongst the 10 most water-risk-prone countries out of a total of 142 countries (Schwerter & Sairafi, 2023). The country has been facing an extended drought for the past 13 years, driven by high temperatures and a significant lack of precipitation (Cochilco, 2023). According to the Chilean Ministry of the Environment, Chile is extremely vulnerable to climate change and, therefore, Chile is very likely to experience increased occurrences and intensity of extreme events such as river and coastal floodings and prolonged droughts (Schwerter & Sairafi, 2023). Climate projections suggest that precipitation rates will decrease significantly over the next decades in Chile, with an anticipated decrease of 15-20% in the north of Chile and a decrease of 20-40% in the central areas (Alvez et al., 2020; Williams, 2017).

Chile’s water scarcity is not uniform across the country, it varies significantly by region. These vast imbalances are the result of several factors including variations in precipitation, groundwater storage and glacial meltwater (Alvez et al., 2020), each contributing to significant disparities in water availability between regions. This uneven distribution of water resources along Chile’s latitudinal gradient is starkly illustrated by the disparity in freshwater availability per capita, as shown in Figure 5. The northern regions, including the Atacama Desert, are persistently short of water. Central Chile, which comprises the bulk of major cities, such as Santiago and Valparaíso are experiencing decreasing water availability, mostly due to less rainfall and excessive extraction of groundwater. In contrast, more precipitation occurs in the southern region, but the possibility of water resources there is difficult to exploit due to the challenging terrains and sparse populations. More in detail, in the northern regions, freshwater availability is as low as 52 cubic meters per capita per year, while in the southern regions, it reaches an as high as 2,993,535 cubic meters per capita per year (Alvez et al., 2020; Williams, 2017; Pino et al., 2015).

On the demand side of water in Chile, accounting for around 72% of the water consumption nationwide, the agricultural sector is the largest water consumer, followed by household and industrial activities, accounting for 12% and 7%, respectively (DGA, 2024). While the geographic distribution of water in Chile water is significantly unequal, the water demand varies considerably as well. Due to the high population and high concentration of agricultural and industrial activities, the water demand is at its highest in the central region. On the other hand, mining is the largest water consumer in the northern regions, which are the most water-stressed regions in Chile. Figure 5 shows the geographical distribution of water availability across Chile.

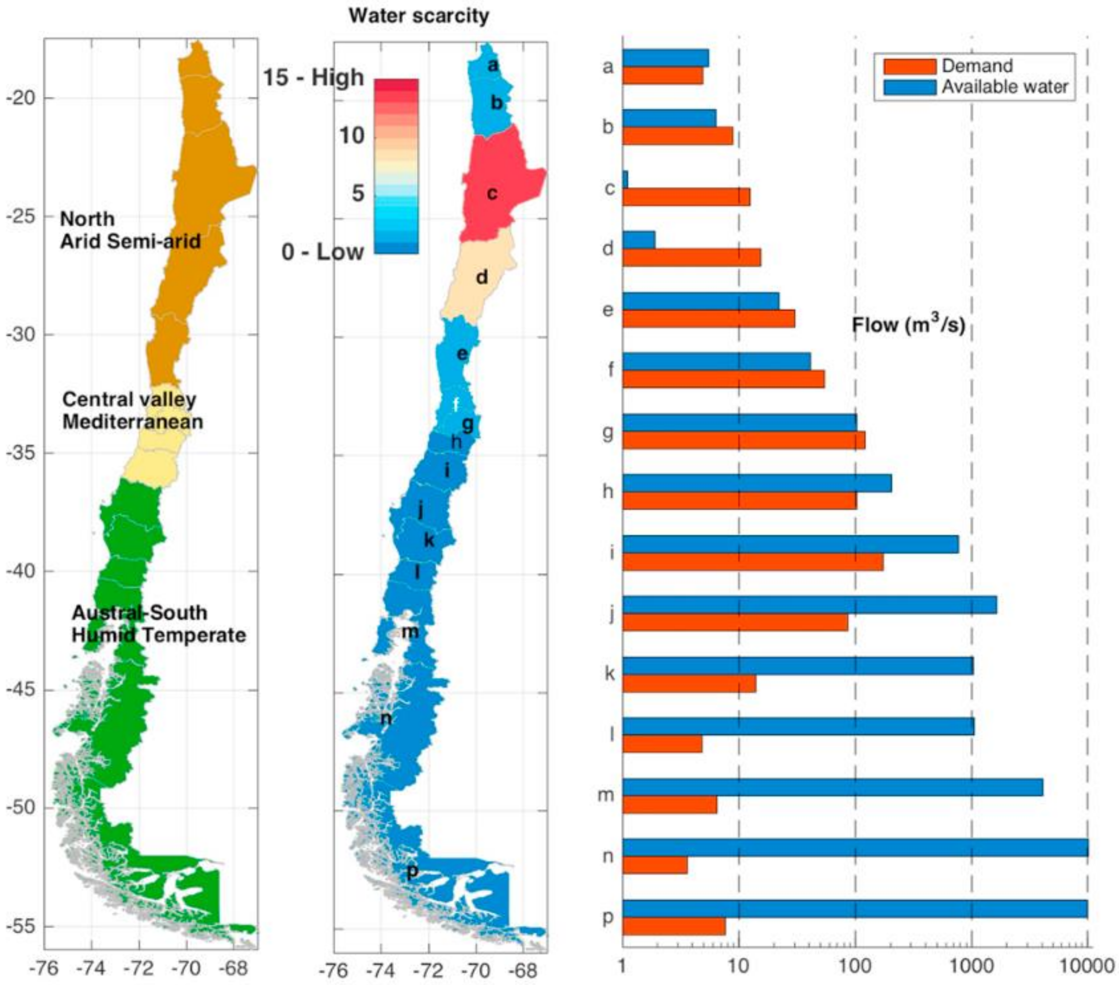

Figure 5: Climatic zones, water scarcity and water supply and demand by regions in Chile (Alvez et al., 2020)

In response to the water scarcity issue, the Chilean Government launched a new project called "Plan de Adaptación al Cambio Climático para los Recursos Hídricos (PACC-RH)", which translates to Climate Change Adaptation Plan for Water Resources, which tackles the problems and the opportunities related to water within the country (*Plan de Adaptación al Cambio Climático*). In Chile, the Dirección General de Aguas (DGA), the General Department of Water, is responsible for regulating water use concessions, ensuring sustainable management of the country's water resources. In 2024, the DGA plans to significantly expand the so-called *no-take* zones, areas where water extraction is heavily restricted or prohibited. According to the DGA's director, these zones will increase from 30 to at least 70. Within these *no-take* zones, no new water use licenses can be issued, and any extensions of existing permits must receive approval from environmental authorities. This expansion is part of a broader strategy to protect critical continental water resources and address environmental concerns in Chile (DGA, 2024). This measure reflects the urgent need to conserve water in response to the prolonged dry season and its severe impact on the environment and industry.

2.4.1 Water Scarcity and the mining industry in Chile

As a result of the water scarcity challenge, Chile’s economic resilience is being tested, especially in the central and northern regions. These areas play a fundamental role in the country’s economic development but are characterized by rising sectoral conflicts, environmental degradation and adverse effects on social and economic growth (Alvez, Astudillo et al., 2023; Schwerter & Sairafi, 2023). The geographic characteristics of these areas, as well as the private nature of the water market in Chile, place the mining industry in direct conflict with the agriculture industry as well as local communities, which leads to increased pressures and socio-environmental risks (Alvez et al., 2020; Garcia-Zavala et al., 2023). While mining activities account for only 4% of national water consumption, as shown in Figure 6A, agriculture dominates the consumption with 71%, followed by domestic consumption at 12%. However, mining accounts for around 51% of water consumption in water-scarce regions such as Antofagasta (Alvez et al., 2020; Garcia-Zavala et al., 2023). The high demand for mining for water leads to disproportionate consumption profiles of water within arid regions, which have, as a result, strong social and environmental impacts. Competition for scarce water resources also increases, and the quality of water decreases, leading to increased mining tailings-related risks that serve as a spark for opposition to the industry, both locally and internationally (Astudillo et al., 2023). Furthermore, it is expected that the water consumption of the mining industry will increase as a result of the increasing demand for copper and lithium as well as the decreasing ore grade (Alvez et al., 2020).

In the mining sector, Cochilco (2023) identifies the phases of ore concentration, which include crushing, grinding, flotation, classification, and thickening, as the most water-intensive activities. This process accounts for 59% of the total water consumption in the mining industry, as illustrated in Figure 6B. According to Figure 6C, seawater has become the most widely used water source in mining, reaching 34% of the total normal consumption (DGA, 2017). Cochilco also predicts a higher water consumption in copper mining in Chile, achieving 23,6 m3/s in 2030, which is around 31% more than in 2022. By 2034, seawater is projected to account for approximately 70% of the total water supply needed to meet this demand (DGA, 2017). Antofagasta, the region where this dissertation's simulation is conducted, remains one of the largest water consumers, with a shift from continental water to increased seawater usage driven by desalination projects. Currently, eighteen desalination plants operate along Chile's coastline, with many located near towns and cities, though most are relatively distant from mining sites. Of these, thirteen supply water to the mines, while the others focus on producing drinking water (Alvez et al., 2020). Using seawater as a water source for copper mining is a viable strategy to enhance sustainability in the mining sector. However, it is crucial that these desalination projects adopt sustainable practices, particularly in managing energy consumption and waste generation (Comisión Chilena del Cobre, 2024).

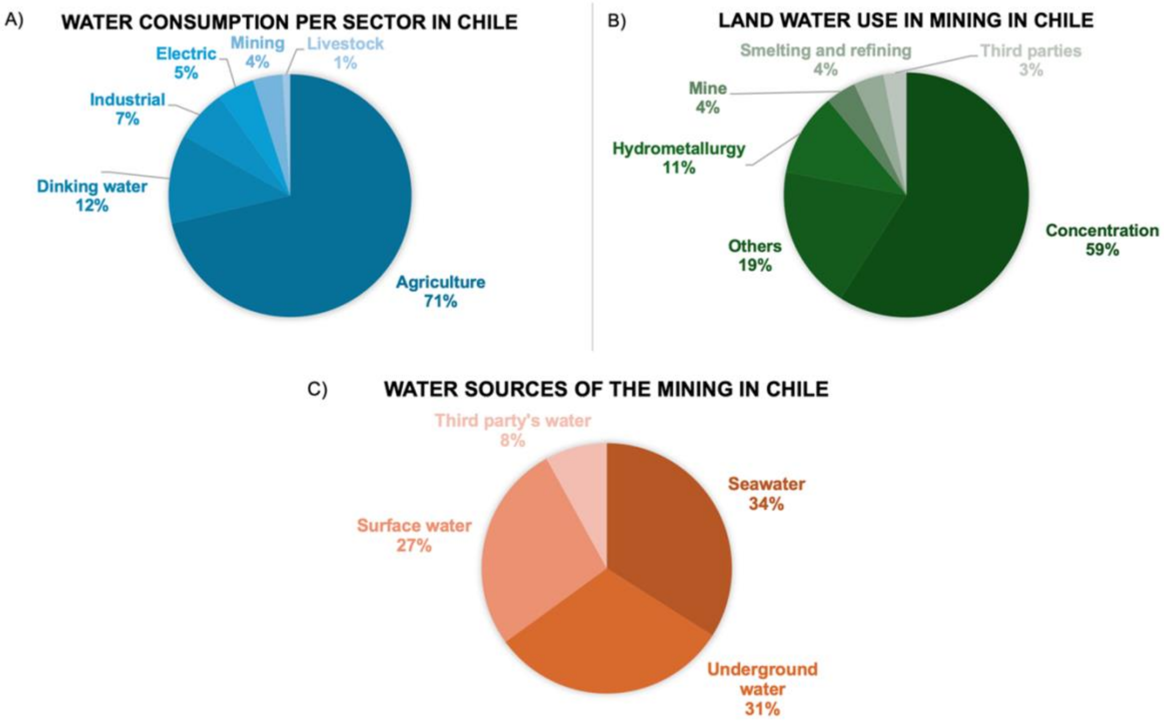

Figure 6: A) Water consumption per sector in Chile. B) Land water use in mining in Chile. C) Water sources of the mining in Chile. (DGA, 2017 and Comisión Chilena del Cobre, 2024).

In the context of evaluating different water sources for copper mining operations, the choice between raw seawater and desalinated seawater presents distinct advantages and challenges. When considering raw seawater as the sole water source, several significant advantages and challenges must be addressed. The primary distinction between desalinated water and seawater lies in their environmental impacts related to tailings. Seawater presents an advantage in this regard, as it does not generate acid mine drainage (AMD) like desalinated water (Texeira et al., 2023).

One of the primary issues is corrosion. The high salinity and ionic strength of raw seawater are known to accelerate the corrosion of metallic components within processing facilities. According to literature, seawater's chloride ions are particularly aggressive. This accelerates maintenance needs and shortens the lifespan of equipment. Mitigation strategies include the use of corrosion-resistant alloys and coatings, such as HDPE pipelines (Moreno et al., 2011). Additionally, the management of the pH is affected by the buffering capacity of raw seawater, which complicates the regulation of the pH during flotation processes. Seawater presents high concentrations of carbonate and bicarbonate ions, stabilises pH levels, reducing the need for lime, which is typically used with freshwater to create alkaline conditions (Suyantara et al., 2023). Instead, sodium metabisulfite is required in substantial quantities to neutralize the buffering effect and maintain pH levels conducive to effective flotation. It is used to counteract the high magnesium content in seawater, which influences the flotation process. In seawater-based operations, sodium metabisulfite acts as a depressant, specifically targeting pyrite without altering pH, as opposed to its effect in freshwater flotation processes, where lime is used for pH adjustment. As recent studies indicate, the application of sodium metabisulfite in high-magnesium conditions facilitates the depression of pyrite, thus improving mineral separation and overall process efficiency (Suyantara et al., 2023). A disadvantage related to pumping raw seawater from the ocean to high-altitude processing plants is the energy consumption. This process involves considerable energy consumption, given the challenges associated with transporting water over long distances and elevations. The energy costs associated with this process can be substantial, representing a significant portion of operational expenses (Moreno et al., 2011). Incorporating these costs into the LCA and exploring energy-efficient pumping technologies are critical for managing operational expenses.

The second scenario involves the use of desalinated seawater, which introduces its own set of advantages and disadvantages. Desalination is a highly energy-intensive process, requiring significant power to remove salts and other impurities from seawater to produce fresh water suitable for industrial use. This process not only demands substantial energy resources but also results in the production of brine waste, which poses serious environmental concerns (Jones et al., 2019). A major environmental concern arises from the large volume of brine produced in the desalination process that requires management. Jones et al. (2019) mention that brine management is both economically expensive and technically difficult, and hence, most desalination plants discharge untreated brine directly into the environment. This brine, which contains high concentrations of salts and other chemicals, can negatively impact marine ecosystems by increasing salinity levels and harming aquatic life. To address these challenges, it is crucial to evaluate and mitigate the environmental impacts of brine disposal and consider advanced desalination technologies that enhance energy efficiency and reduce brine production. Addressing these challenges, research studies have demonstrated that there are economic opportunities associated with brine, such as commercial salt and metal recovery and the use of brine in fish and halophyte production systems. Such approaches can potentially convert brine from an environmental problem into an economic opportunity. There is a pressing need to translate such research into practical applications, allowing industries to mitigate the negative environmental impacts of brine while also deriving economic benefits (Jones et al., 2019).

Chemical management in desalinated seawater differs from raw seawater due to its lower ionic content. However, lime is still required to adjust the pH to the optimal range for the flotation process. The accurate dosing of lime and the continuous monitoring of its impact on flotation efficiency is crucial for minimising reagent wastage and maintaining the overall efficiency of the process. Operational performance can also vary when using desalinated seawater, as differences in flotation performance compared to raw seawater may affect reagent consumption and overall process efficiency. These variations necessitate continuous assessment and adjustment of flotation parameters to ensure optimal efficiency (Minera Spence S.A., 2015). Desalination plants, which are increasingly used as a solution due to water scarcity, come with several significant disadvantages. Firstly, they operate within complex and often ambiguous legal, institutional, economic, and political frameworks, as seen in Chile.

Additionally, these legal uncertainties complicate the governance of water resources, contributing to shifting hydro-geographies and posing challenges to effective water governance in mining territories. These issues underscore the broader socio-legal challenges that desalination technologies face, particularly in regions where water governance is already contentious (Campero & Harris, 2019).

2.5 Conclusions

This section concludes that the global copper market is essential for industries such as construction, electronics, and renewable energy. The importance of copper arises from its unique properties and increasing demand, particularly in emerging economies and sustainable technologies. However, the industry faces challenges from fluctuating prices, supply-demand imbalances, and geopolitical issues. Regarding Chile, the country plays a crucial role in global copper production, contributing around one-third of the world's output due to its geological context, located in a tectonic subduction zone, providing abundant copper deposits, particularly in the Chilean Andes. Chile's leadership in copper supply is favoured by its advanced mining technologies, and the future sustainability of copper supply will depend on technological advancements and socio-economic changes. One of the most pressing challenges for Chile is water scarcity, as the country ranks among the top ten globally for water stress. Prolonged droughts and reductions in precipitation impact multiple sectors, including mining, creating conflicts with agriculture and local communities. Sustainable water management strategies, such as using seawater through desalination, are essential for Chile's future.

3. State of the Art

This chapter is divided into four sections. Section 3.1 focuses on the LCA literature review, followed by section 3.2, which specifically highlights LCAs in the mining industry, covering their methodologies and approaches. Section 3.3 tackles water use in the copper mining sector, presenting studies and recommendations for facing the challenges found. The state-of-the-art conclusion includes a brief conclusion of all the subsections.

3.1 Life Cycle Assessment (LCA)

Life Cycle Assessment is a structured methodology that involves a number of steps and is employed to compile an inventory of the environmental impacts that result from the processing and production of products over their life cycle (Sala et al., 2021). These evaluations cover all the stages from raw material acquisition, processing, manufacturing, distribution, use, repair and maintenance, and disposal and recycling back into raw material (Hayes et al., 2023). LCA plays a role in understanding the environmental impact of products and making informed decisions in relation to sustainable development. Overall, LCA finds great application within industrial sectors for bettering their environmental performance, regulatory compliance, and sustainable product development.

Life Cycle Assessment (LCA) is inherently distributed over four distinct stages, which together offer an exhaustive evaluation of the environmental impacts of a product. The four stages are; Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. All four phases play their role in the process of assessment. The Goal and Scope Definition outlines the structure of the study, including its purpose, definition of the area, and key parameters. During the LCI phase, input and output data across the life cycle of the product are systematically collected and quantified. The LCIA stage is an interpretation process applied to the inventory data to evaluate potential environmental impacts and categorise them into specific impact areas. The last Interpretation phase combines the results of the previous phases to come up with conclusions, find the major problems, and give suggestions on how to improve. The general framework for an LCA is predetermined by the International Organization for Standardization (ISO). The ISO 14040 and 14044 standards provide the backbone for performing LCAs. Refer to Figure 7, which is a schematic diagram of the LCA frameworks in accordance with the ISO standard.

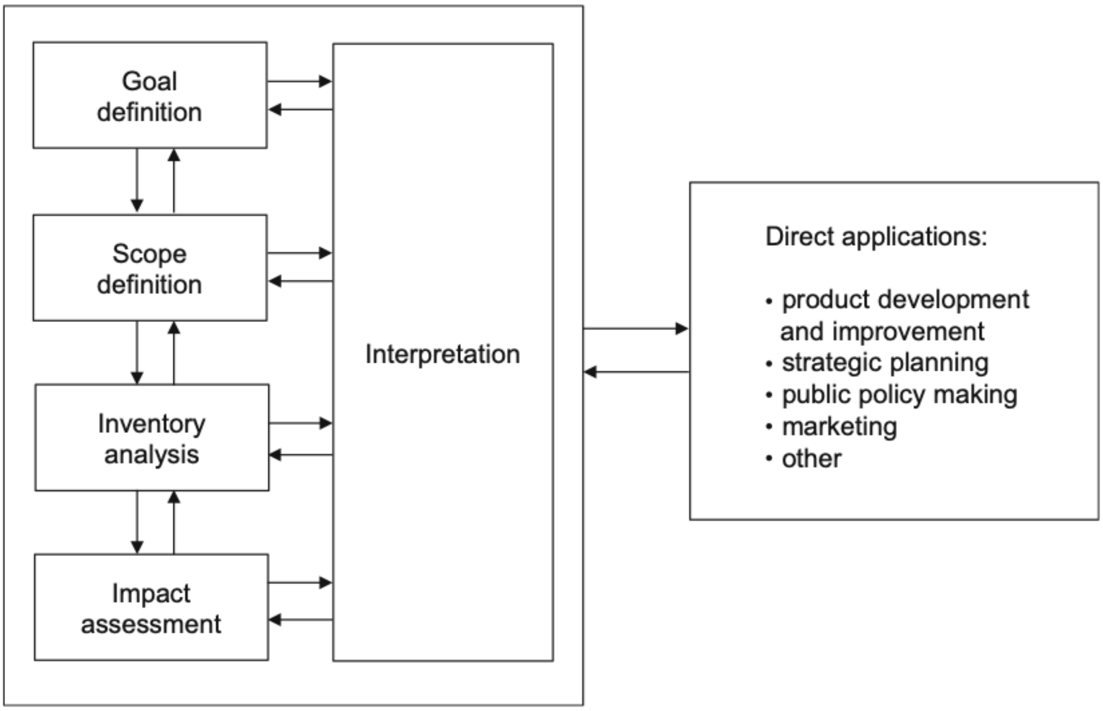

Figure 7: Stages of Life Cycle Assessment (Hauschild, 2018)

More in detail, the first stage of LCA involves defining the goal and scope of the assessment. It defines the goal of the study, which is to identify the product with the best performance or the weak points that can provide opportunities for improvements. Other major elements that are checked are defining the functional unit, a quantified description of the performance of the product, setting the system boundaries, helping to determine which processes are going to be included in the analysis, and the assumptions and limitations. Defining the goal and scope of LCA ensures setting the focus of the study and keeping it relevant (Haque, 2020).

The Life Cycle Inventory (LCI) is the core of LCA analyses because it includes data collection and analysis. This involves an inventory that lists and quantifies all of the energy and material inputs and environmental releases resulting from a product's life cycle. The LCI stage is very intense in data collection: from databases, literature sources, and direct measurements. Inventory analysis identifies and quantifies all inputs and outputs to a system, and it leads to a most comprehensive data set for the following impact assessment step (Haque, 2020; Kalverkamp et al., 2020).

During the Life Cycle Impact Assessment (LCIA) stage, the information from the Life Cycle Inventory (LCI) is analysed to evaluate environmental effects by following ISO guidelines. Impact categories are chosen based on specific objectives, such as climate change and resource depletion. Inventory data is then allocated to these categories for effective analysis. The next step involves characterising each inventory item based on its impact category using factors like global warming potential.

Damage assessment converts impact categories into broader endpoint categories like human health and ecosystem quality to illustrate long-lasting consequences. Normalisation compares impact category results to a benchmark value for easier comparison. Weighting assigns importance to impact categories, allowing for a combined overall score.

The final step converts weighted results into a single score, providing decision-makers with a comprehensive measure of environmental impact. The LCIA phase offers insight into the environmental effects of a product or process, supporting decision-making to minimise these effects. The data collected at the LCI stage is processed to evaluate and quantify potential environmental impacts. The process consists of the inventory data classified under various groups and indicators of the environmental impact, such as global warming potential, acidification, eutrophication, and resource depletion. Classification means assigning inventory data to the respective impact categories, whereas characterisation represents the quantification of the contribution of each inventory item to the impact categories. The LCIA phase assesses the environmentally relevant impacts associated with a product or process and helps in understanding the magnitude, extent, and localised or widespread nature of the effects of the analysed activity. The International Reference Life Cycle Data System (ILCD) Handbook, developed by the European Commission's Joint Research Centre (JRC), provides a detailed framework and recommendations for these impact categories, which is called Environmental Footprint (EF). Table 1 illustrates the impact categories EF framework and their corresponding indicators as outlined by the European Commission.

Table 1: Impact categories and their corresponding indicators by the European Commission (European Commission, 2021)

Impact Category	***Impact Category Indicator***	***Unit of measure***	***Description***
Climate Change	Global Warming Potential (GWP100)	kg CO_2 eq	Increase in the average global temperature resulting from greenhouse gas emissions (GHG)
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation
Human Toxicity (Cancer effects)	Comparative Toxic Unit for humans (CTUh)	CTUh	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured
Human Toxicity (Non-cancer effects)	Comparative Toxic Unit for humans (CTUh)	CTUh	Impacts of toxic substances on human health, excluding cancer-related effects.
Particulate Matter/Respiratory Inorganics	Intake fraction for fine particles (kg PM2.5-eq/kg)	Disesease Incidence	Impact on human health caused by particulate matter emissions and its precursors (e.g. sulfur and nitrogen oxides)
Ionising Radiation (Human health)	Human exposure efficiency relative to U235	kBq U-235 eq	Impact of exposure to ionising radiations on human health
Photochemical Ozone Formation	Tropospheric ozone concentration increase	kg NMVOC eq	Potential of harmful tropospheric ozone formation (“summer smog”) from air emissions

Impact Category	**Impact Category Indicator**	**Unit of measure**	**Description**
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Acidification from air, water, and soil emissions (primarily sulfur compounds) mainly due to combustion processes in electricity generation, heating, and transport
Eutrophication (Terrestrial)	Accumulated Exceedance (AE)	mol N eq	Accumulation of nutrients, particularly nitrogen compounds, in terrestrial ecosystems.
Eutrophication (Freshwater)	Fraction of nutrients reaching freshwater end compartment	kg P eq	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilizers, combustion, sewage systems
Eutrophication (Marine)	Fraction of nutrients reaching marine end compartment	kg N eq	Nutrient enrichment, especially nitrogen, in marine environments, promoting algal blooms that reduce oxygen levels (hypoxia) and disrupt marine ecosystems, affecting marine life and water quality.
Ecotoxicity (Freshwater)	Comparative Toxic Unit for ecosystems	CTUe	Impact of toxic substances on freshwater ecosystems
Land use	Soil quality index, representing the aggregated impact of land use on: Biotic production; Erosion resistance; Mechanical filtration; Groundwater replenishment	Dimensionless (pt)	Transformation and use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil, filtration capacity, permeability
Water use	Weighted user deprivation potential	m3-world eq	Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity
Resource use, minerals and Metals	Abiotic resource depletion – ADP ultimate reserves	kg Sb eq	Depletion of non-renewable resources and deprivation for future generations
Resource use, fossils	Abiotic resource depletion, fossil fuels – ADP-fossil	MJ	Depletion of fossil fuel resources, such as coal, oil, and natural gas.

The final step for the LCA is interpretation, where the outcomes of the LCI and LCIA are analysed to make conclusions and recommendations. More commonly, it includes identification of important issues according to findings, evaluation of robustness and limitations of the study, and consideration of sensitivity and uncertainty of results. The interpreting phase should aim to develop insights that are clearer and also much more useful for inference in decision-making, improving environmental performance, and communicating with stakeholders. Effective interpretation is crucial in the translation of LCA results into implementation strategies for sustainability (Haque, 2020).

3.2 LCAs in Mining

LCA is a popular analysis in the mining industry since it can study multiple scenarios and assess their risk and opportunities. Chile has been popular for developing LCA case studies because it is a major global copper supplier and a country under high water stress (Cochilco, 2023). Different LCAs related to copper mining had been done, assessing multiple scenarios with different focuses, such as environmental impacts of copper tailings, consequences on ecosystem services from copper mining, emissions to air calculation, energy use, etc. All of these studies help to describe the copper mining process in more detail.

Adrianto et al. (2023) conducted a prospective LCA to quantify the environmental impacts of copper tailings reprocessing in the EU based upon future scenario narratives that would model various possible outcomes. They focused on sulfidic copper tailings as a case study and assessed the potential for reprocessing to mitigate greenhouse gas (GHG) emissions and toxicity impacts by 2050. The results of this study indicate that the reprocessing of tailings has the potential to offer up to 2% of the future European demand for copper and decrease multiple environmental impact indicators. Nevertheless, the analysis revealed that there are trade-offs concerning the impacts of climate change and ecotoxicity across various reprocessing scenarios, which are shaped by technological pathways, market fluctuations, and substituted products. The study concludes that although reprocessing can significantly contribute to mitigating climate impacts, further demand-side management efforts are required to meet the 1.5°C climate target of the Paris Agreement. Their work provides a scientific basis for decision-making towards more sustainable reprocessing and valorisation of sulfidic tailings in the copper industry (Adrianto et al., 2023).

Blanco et al. (2018) developed a framework to incorporate ecosystem services (ES) into LCA demonstrated by a case study of mining in Chile. The framework partitions the modelling steps into different phases of LCA, starting with physical models to assess how industrial processes transform physical units of ecosystems, followed by ES models to quantify the losses or gains of ES per ecosystem unit. Economic valuation methods were then used to normalise and weigh the total ES losses or gains. The framework was demonstrated throughout a case study on water extraction by the mining industry in Chile, comparing the ES losses associated with the transformation of wetland and coastal ecosystems. The study found out that the proposed framework advances current LCA methods by addressing spatial and temporal variability in ES production and incorporating socioeconomic aspects of ES use, facilitating the coupling of LCA with other ES databases under development.

Narita et al. (2001) conducted a Life Cycle Inventory (LCI) analysis of the copper production system in Chile, using the Life Cycle Assessment (LCA) technique to evaluate CO_2 and SO_2 emissions. The study compared the environmental impacts of pyro-metallurgical and hydro-metallurgical copper production, highlighting significant differences in emissions between the two processes due to the use of sulfuric acid in the hydro-process. The analysis also noted that the desulfurisation efficiency in Chile's pyro-metallurgical production is lower compared to the one in Japan. While the study focused on emissions, it acknowledged the need for further evaluation of environmental impacts on soil and water, which were not covered in this research.

Kelly et al. (2015) updated the LCI data for copper in the GREET™ Model, which analyses greenhouse gases, emissions, and energy use in transportation. The report emphasises the importance of using current, open-source data for accurate LCAs and focuses on copper wire's role in the automotive industry. The authors Castro-Molinare et al., (2014) developed an LCA model for copper extraction and processing, incorporating waste management and emissions to air, water, and soil. This model addresses limitations in conventional LCA tools, which often overlook detailed unit process emissions and waste management. The paper includes a case study of a Chilean mining operation and evaluates how variations in parameters like ore grade and energy sources affect the LCA impact scores.

Pena & Huijbregts (2013) quantified the continental water footprint (WF blue) for copper extraction and production in the Atacama Desert, focusing on both copper sulfide and oxide ores. It found out that refining copper from sulfide ores consumes significantly more water than from oxide ores. The majority of water in sulfide ore processing is lost through seepage, accumulation, and evaporation, while in oxide ore processing, water loss mainly occurs through evaporation during heap-leaching. The study suggests that water use could be reduced by improving water recovery and using seawater for copper production, which could decrease the WF blue by up to 62%.

China is also a very interesting country in terms of copper processing, since it is where The majority of smelting activities are performed there. For example, Lu et al. (2022) analysed the Life Cycle environmental impact of copper concentrate production in China, focusing on a typical copper sulfate mine. Using SimaPro with the ReCiPe 2016 method and Monte Carlo simulations, the assessment revealed that marine ecotoxicity had the highest impact, followed by freshwater ecotoxicity and human health concerns. Key contributors included mining, backfilling, and electricity generation, with cement production, blasting, on-site emissions, and electricity generation identified as critical processes. The study highlighted controlling on-site emissions and reducing cement production pollution as effective measures to mitigate environmental impacts and proposed technical and management strategies for cleaner metal industry practices.

Table 2: Summary of LCA Studies on Copper Production and Processing

Country & Mineral	***Sofware***	***System boundary***	***Method***	***Author***
EU, Cu Tailings	Premise	Copper tailings reprocessing	LCA (ReCiPe)	Adrianto et al. 2023
Chile, Cu	InVEST	Framework for ES	LCA (unspecified)	Blanco et al. 2024
Chile, Cu	-	Cu production	LCA (CML)	Narita et al. 2001
Chile, Cu	GREET	Cu production	LCI (GREET)	Kelly et al. 2015
Chile, Cu	NIRE-LCA ver.3	Cu production	LCA (CML)	Narita et al. 2001
China, Cu	SimaPro	Cu production	LCA (ReCiPe)	Lu et al. 2022
Chile, Cu sulphide and oxide ores	Ecoinvent	Contiental water footprint for Cu extraction and production	LCA (Unspecified)	Pena & Huijbregts 2013
Chile, Cu	GaBi 6	Cu extraction and processing with waste management	LCA (ReCiPe)	Castro-Molinare et al. 2014

Despite the number of studies conducted, there is still an obvious lack of information in the literature on the environmental effects of using seawater compared to desalinated water in copper mining activities. The majority of current research, as outlined in Table 2, examines emissions, tailings management, and overall water use. However, there is a lack of thorough analysis comparing these specific water sources in copper beneficiation. The LCA presented in this dissertation addresses the gap in the current knowledge regarding the environmental impacts of using seawater as compared to desalinated water in copper mining and beneficiation operations. Although extensive research on various aspects of copper production exists, there is a lack of comprehensive studies comparing these two water sources, specifically within the context of copper beneficiation. This research provides a detailed evaluation of how seawater and desalinated water affect critical environmental performance indicators, such as water consumption, energy use, and emissions. By comparing these two scenarios, the study provides insights into their respective advantages and disadvantages for sustainability in copper mining. This is particularly pertinent for Chile, a nation facing acute water stress and heavily dependent on copper mining. The findings of this dissertation are essential for developing strategies that minimise environmental impact and optimise resource management, thus contributing to more sustainable practices in one of the world’s most water-intensive industries (Aramendia et al., 2023).

3.3 Water use in mining

Copper mining generally includes several important stages in transforming raw ore through into copper concentrate, with further refining. These stages are mining or extraction, crushing and grinding, flotation, and dewatering. During mining, copper ores are excavated either by open-pit or underground methods. After extraction, the ore is sent to a processing plant for crushing into smaller pieces and then grinding into a fine powder during the processes of crushing and grinding. This stage also requires water at this stage to reduce dust and enable the movement of crushed material. To illustrate, milling operations depending on the type of ore can use a volume in the range from 0.3 to 1.0 cubic meters per tonne of ore (Franks et al., 2013). This alone accounts for a substantial fraction of the overall copper mining water footprint. During flotation, the ground ore is mixed with water and reagents in flotation cells in order to allow the separation of copper minerals from the worthless material. Flotation is the phase that consume the most water from the whole processing process, using 60% of the total water used for the mining operation (Cochilco, 2019). The resulting slurry, which is a mixture of ore, water, and reagents, is then subjected to a process where air is blown into it, giving rise to bubbles that serve to carry the copper-rich minerals to the surface. These are skimmed off to form a copper concentrate, usually containing between 25% to 35% copper (Delbeke & Rodriguez, 2014). Large volumes of water are required in this stage of the operation for maintaining the slurry consistency, as well as clean water inputs for chemical additives, which are essential to the efficient selective recovery of the copper minerals. This large amount of water use in these stages allows for efficiency in the separation process (Abbadi & Mucsi, 2024). The last step in producing the copper concentrate is the dewatering of the copper-bearing material. During this process, the copper concentrate is filtered and dried to decrease the water content for transportation easily to the facilities where smelting will be conducted. Water will be very important in those stages in controlling dust, ease of ore moving, and separating valuable copper from waste materials (Mussey, 1961).

There have been scientific and technological advancements in water reduction within copper mining in response to the high water demand in copper mining and the associated environmental and social impacts. Numerous life cycle assessment (LCA) studies have been carried out to establish a framework for evaluating the environmental effects of water usage in mining operations. A publication by Molinaire (2014) presents an LCA for copper production with the scope of extraction and processing. The study identifies water use as a priority environmental issue in areas such as Northern Chile, where freshwater is scarce. Results emphasise impacts that result from water-intensive processes like grinding and flotation, which deplete regional water supplies and stress the ecosystems of communities with limited water supplies. In addition to highlighting the need for water-saving strategies, this study identifies other procurement alternatives, which include desalination and water reclamation, in order to reduce ecological impacts due to copper extraction in areas with low water availability. Additionally, studies such as Northey et al. (2013) and Memary et al. (2012) have conducted LCA studies to quantify the water footprint of copper production, with the focus on ore processing and tailings management as the critical areas related to water consumption within the copper mining activities. Northey et al. (2013) found that water is essential in the beneficiation process, which is used in ore grinding, transportation of concentrate slurries, and flotation. The water consumption of these processes ranges widely due to the ore grades and also due to specific processing techniques applied. In addition, for tailings management, huge amount of water is required for transportation and storing purposes, which is another major area of concern. The water intensity also differed between different regions. Activities conducted in arid countries, such as Chile and Australia, for instance, showed higher levels of water use than those activities carried out in colder countries, such as Canada and Finland. The research conducted by Memary et al. (2012) points out various discoveries about the use of water in mining activities, stressing the substantial quantities needed, especially for milling and smelting tasks. Water consumption rates differ according to the kind of mining activity (open cut versus underground) and the methods utilised. Escalating production and decreasing ore quality commonly result in greater water usage, putting pressure on nearby water sources, particularly in regions with limited access or where mining affects nearby ecosystems. While the main concern is greenhouse gas emissions, the research suggests that mining operations can also harm water quality by potentially contaminating local water sources with runoff, endangering aquatic ecosystems and human health. In order to address these impacts, it is crucial to adopt effective environmental management practices, such as enhancing water efficiency and implementing more efficient management strategies to lessen the environmental impact of mining operations.

Lastly, "the implementation of monitoring systems enables the measurement of water use and the identification of further savings opportunities". In addition, monitoring, coupled with automation, has allowed copper mining companies to optimise water use. Moreau et al. (2021) discuss how automation systems could contribute to saving water through the optimisation of ore processing activities. This would make it possible to monitor and manage in real time the flow of water, hence improving with greater accuracy and efficiency the use of the water. Collectively, these measures not only conserve freshwater resources but also contribute to the sustainability of mining operations by mitigating environmental impacts associated with water extraction and usage.

Other authors, such as Lagos et al. (2018), tackled water use from another perspective, which is the continuously increased use of water in copper mining as a result of the diminishing high-grade ore reserves. As the quality of ore declines, a more considerable amount of material needs to be processed to produce an equal quantity of copper, consequently raising water needs for activities such as grinding, leaching, and flotation. In Lagos et al. (2018) study the highlight is that as copper mines get older, they use more water because they have to process more significant amounts of ore containing less copper. This pattern is especially noticeable in mines that have been operating for a long time, as lower ore quality puts more pressure on water supplies, particularly in regions with limited water, such as Chile.

In regions like Northern Chile, where freshwater resources are scarce, the use of desalinated water has become more dominant. Leiva González & Onederra (2022) discuss environmental management strategies in the Chilean copper mining sector, with a particular emphasis on the adoption of desalination to offset freshwater scarcity. Probably the most visible development in water management for Chilean copper mining is the greater reliance on both raw and desalinated seawater. According to a forecast conducted by Cochilco 2023, by 2029, the share of seawater in total water usage by the copper mining sector would reach 60%, especially with more and more companies investing in seawater pipelines and desalination plants to reduce reliance on scant freshwater resources (P. Vargas, 2019). For example, the Escondida Mine, one of the world's largest copper producers, has already integrated desalination into its operations. This desalination facility processes seawater from the Pacific Ocean into freshwater for use in copper mining and concentrate production. As of 2023, the plant supplies 100% of the mine's water requirements, showcasing a model of freshwater-independent operations (The Cooper Mark, 2023). Desalination enables the mining industry to decrease its consumption of freshwater resources, but access to energy-intensive and higher-cost desalination is a barrier to wider adoption.

3.4 Conclusion of the State of the Art

This state-of-the-art review emphasises the important role LCA plays in analysing environmental impacts at each stage of copper production. The review of existing research developed in this work proves that LCA has become an important tool to understand the environmental footprint of copper mining since it allows multiple scenarios to be considered, all with risks and opportunities. Notably, studies on LCA in copper mining have primarily focused on emissions, energy use, tailings management, and water use. Chile is a prime location for such analyses due to its status as a leading global copper supplier and its severe water stress.

Several gaps in current research were identified, specifically in environmental comparison between seawater and desalinated water in the use of copper beneficiation. There is extensive literature on reprocessing copper tailings, emissions, and ecosystem services; however, such a specific seawater-desalinated water comparison has yet to be discussed. This is particularly crucial with the current state of water stress in Chile and, subsequently, the drive for the mining industry to adopt more responsible means of managing this vital resource.

In addition, the review identified copper extraction as an activity that typically involves a series of critical operations for transforming raw ore into copper concentrate, followed by further refinement. The review shows that water usage in these processes increases the efficiency of separation methods while at the same time placing a high strain on the availability of water. Many studies are investigating improvements in the management of water, such as the application of recycling and water reutilization, as a way of reducing the environmental issues associated with copper beneficiation.

In conclusion, while much progress has been made to date in terms of assessing environmental impacts through LCA for copper mining, this review identified a critical gap by indicating that there is a need for more comprehensive studies related to alternative water sources. This dissertation covers this gap and hence calculates the comparative environmental impacts of seawater and desalinated water in copper mining operations as part of providing momentum for sustainable practices that this resource- and supply-chain-intensive industry so desperately requires.

4. Methodology

In this chapter, the research methodology outlines the adherence to the ISO 14040 and 14044 standards for Life Cycle Assessments (LCAs) by using SimaPro. The methodological framework applied in this study consists of four key steps, each tailored to evaluate the environmental impacts associated with water management in copper processing within Northern Chile. The primary objective is to compare the environmental impacts of using desalinated seawater versus raw seawater in the beneficiation process of copper. The study includes a base case using a copper concentrate dataset and two scenarios involving different water sources: raw seawater and desalinated seawater. The two scenarios will be analysed following four main steps previously mentioned in section 3.4: 1) Goal and Scope definition; 2) Inventory Analysis (LCI); 3) Impact Assessment (LCIA); and lastly, 4) Interpretation.

4.1 Goal and scope definition

The first step in applying LCA involves defining the goal and scope of scenario 1 and 2. The scope is established by outlining the boundaries of each scenario and determining the functional unit to ensure consistency and comparability between the different techniques. This dissertation aims to conduct a comparative LCA of water management strategies in the copper processing plant, focusing on the use of raw seawater and desalinated seawater.

The system boundaries for each scenario are defined from the water extraction for the mining processing to the tailings management stage, focusing on water use. The functional unit for the study is one ton of copper concentrate, allowing for the comparison of environmental impacts across the different water management approaches.

4.1.1 Case Study Definition

The case study represents a copper concentrate plant situated in hypothetic but realistic conditions in the north of Chile, where most of the real copper mines are located (Vargas et al., 2023). In this dissertation, a copper beneficiation plant is studied, where the ore consists of chalcopyrite ($CuFeS_2$), molybdenite (MoS_2) and the gangue is pyrite (FeS_2). Two scenarios will be explored; in both, seawater is extracted from the sea, which is 170km from the processing plant. This water is pumped to the processing plant using a pumping system with three pumping stations (PS) and three pipes, all with the same diameter and length (36 inches). In Scenario 1, the water is pumped directly from the sea to the processing plant. In Scenario 2, the seawater is first transported to a desalination plant located in a coastal area 170km from the processing plant. After desalination, the water is then pumped to the processing plant (Figure 8).

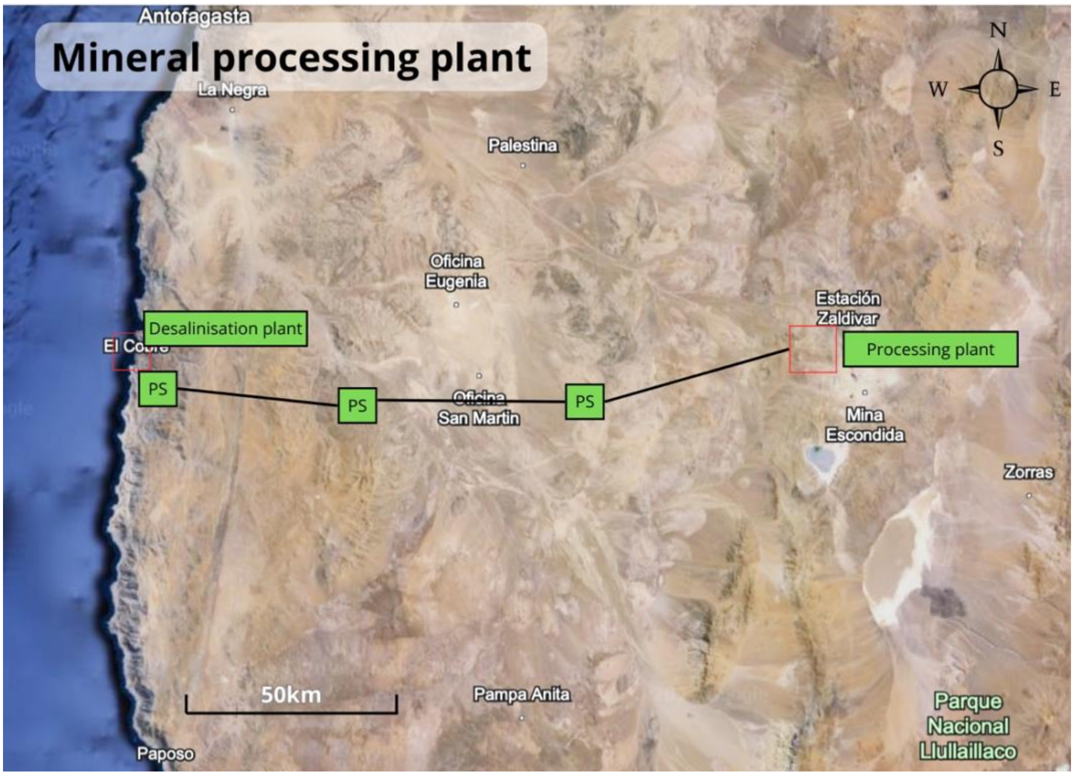

Figure 8: Map of the mineral processing plant simulation located in the north of Chile used for the case studies. PS: Pumping Station (adaptation from Vargas et al. 2023).

4.1.2 Scenario 1: Raw Seawater

Scenario 1 assesses the environmental impacts of using raw seawater as a water source in the copper beneficiation process. This scenario builds upon the base case dataset by incorporating additional data specific to the use of raw seawater (Astudillo et al., 2023). The seawater is sourced directly from the ocean and requires a series of pumping stations to transport it from sea level to the copper processing plant, which is situated at a high altitude, as illustrated in Figure 8.

Scenario 1 illustrates a copper mining and concentration process that utilises seawater as a water resource. Figure 9 illustrates the process that begins with seawater intake from the ocean, which is transported through a network of three high-density polyethylene (HDPE) pipelines to the mining and concentration facilities. This transport infrastructure includes three freshwater pumping stations that are used to move the seawater from its source to where it is needed in the mining operations. The external inputs include materials for constructing the infrastructure, as well as fuels and electricity necessary to power the system. This system's core is the copper mining and concentration process, which directly incorporates seawater into its operations. The use of seawater requires specific chemical agents for flotation and thickening processes to get the best performance. These chemicals are introduced to optimise the separation and concentration of copper from the mined ore. In addition to the chemical inputs, this system stage is energy-intensive, relying heavily on inputs such as fuels and electricity (Astudillo et al., 2023).

The system also includes the management of waste generated during the mining and concentration processes. The main output considered is tailings, which are the leftover materials after the extraction of copper. Tailings are typically handled as a separate waste stream and directed away from the processing site. Additionally, the system produces solid and liquid waste as by-products of both water transport and mining activities (Texeira et al., 2023).

The use of seawater as a primary resource introduces specific challenges, including the chemical challenges associated with using raw seawater, such as corrosion or pH control. Seawater's ionic content necessitates using additional reagents, such as sodium metabisulfite, to manage pH levels and depress the floatability of copper sulfides during the flotation process. These adjustments influence the environmental performance and resource efficiency of the copper beneficiation process (Astudillo et al., 2023).

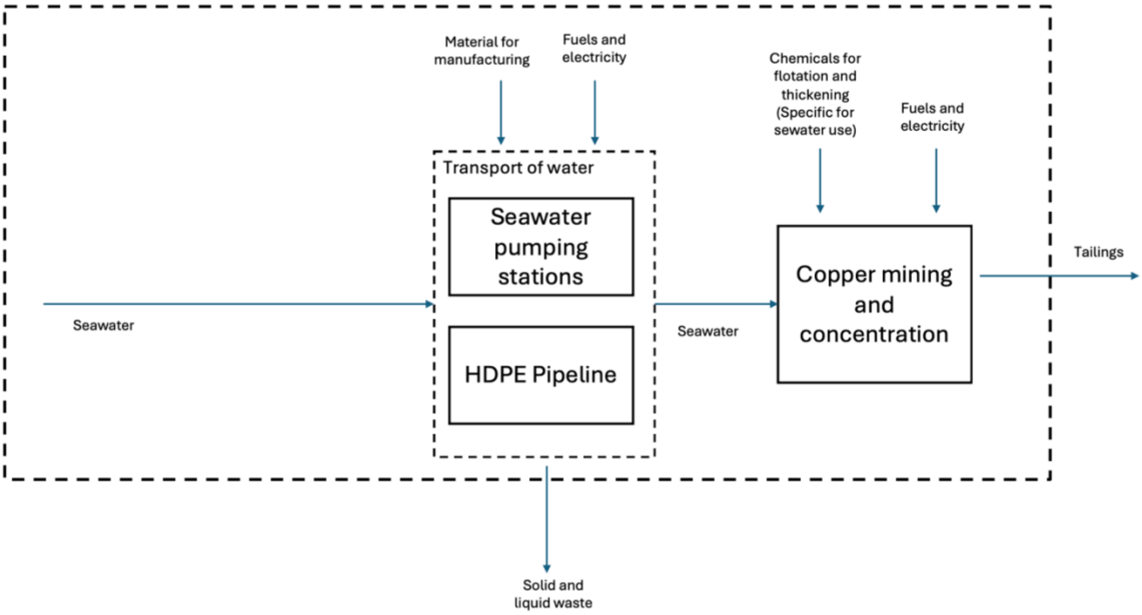

Figure 9: Flowchart for Scenario 1 illustrating the sequence of processing steps and system boundaries for raw seawater.

4.1.3 Scenario 2: Desalinated Seawater

In Scenario 2, the copper mining and concentration process utilises desalinated water instead of raw seawater, which introduces additional components and considerations into the system defined in Figure 10. The process begins with seawater intake from the ocean into a desalination plant, where it is treated to remove salts and other impurities by reverse osmosis technology, producing desalinated water suitable for use in mining operations. The desalination plant relies on significant inputs of electricity to power the desalination process, along with specific chemicals that optimise the operation of the plant (Campero & Harris, 2019). These chemicals aid in efficiently removing salt and other minerals, ensuring the production of high-quality freshwater. The desalination process generates solid and liquid waste, which must be managed as part of the system’s overall waste management strategy. The environmental impacts of this scenario include the energy demands of the desalination process and the associated infrastructure, as well as the management of brine, a byproduct of desalination, which can significantly affect marine ecosystems (Jones et al., 2019).

Once desalinated, water is transported to the copper mining and concentration facilities through an HDPE pipeline network supported by freshwater pumping stations, the same as Scenario 1. These stations ensure the consistent delivery of desalinated water to the mining site. Since the transport of water is the same as Scenario 1, so are the inputs: materials for construction, fuel, and electricity. Regarding the outputs, solid and liquid waste are considered from the water transport.

The copper mining and concentration process, now utilising desalinated water, employs specific chemicals for flotation and thickening that are designed for use with freshwater rather than seawater. Additional reagents are required to adjust the water chemistry for effective mineral processing (Herrera-León et al., 2019). Regarding the inputs, the mining process continues to rely on inputs of fuels and electricity to function effectively, as in Scenario 1. As with the previous scenario, this system also generates waste products, including tailings, which are the residual materials left after copper extraction.

This scenario outlines a more complex system compared to the direct use of seawater due to the introduction of the desalination plant. The desalination process adds an extra layer of resource and waste management, requiring careful consideration of additional inputs such as energy and chemicals and the outputs, including waste products, associated with producing desalinated water. The use of desalinated water instead of raw seawater in the copper concentration process also alters the chemical requirements, making it necessary to adapt the process to suit the different water quality.

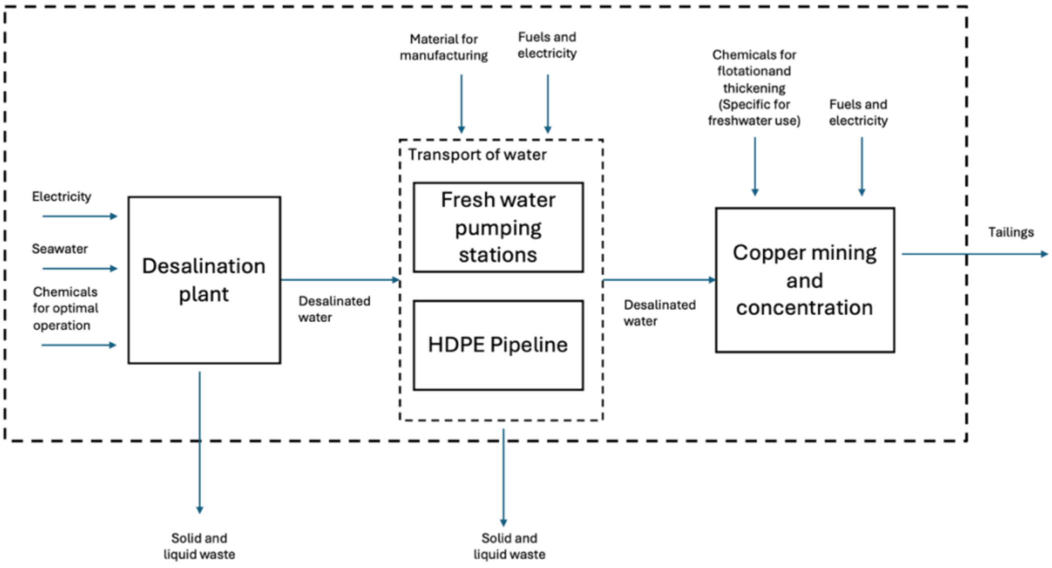

Figure 10: Flowchart for Scenario 2 illustrating the sequence of processing steps and system boundaries for desalinated water.

4.2 Inventory Analysis (LCI)

The second step of the LCA involves collecting and analysing the necessary data to perform the LCA for both case studies. This step will identify and quantify the input and output flows of water, energy, and solids. Data will be sourced from literature, Ecoinvent database, and direct measurements from the mineral processing plants, such as chemicals, where possible.

Table 3: Summary of SimaPro references and associated literature for scenarios 1 and 2 of copper concentration operations, including infrastructure components for water management.

Scenario	***SimaPro reference processes***	***Output Quantity***	***References***
1	*Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore*	*1 kg of copper concentrate*	*(Classen et al., 2009; Northey et al., 2014; Turner & Hischier, 2020)*
	HDPE pipe, DN 900, (SCALED PIPE)| polyethylene pipe production, DN 200, SDR 41 | Cut-off, U	*1 m of polyethylene pipeline*	*Scaled, (Nemecek et al., 2007)*
	Seawater pump, for industrial applications (Scaled) {GLO}| water pump production, 22kW | Cut-off, U	*1 unit of seawater pump*	*Scaled, (Nemecek et al., 2007)*
2	*Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore*	*1 kg of copper concentrate*	*(Classen et al., 2009; Northey et al., 2014; Turner & Hischier, 2020)*
	HDPE pipe, DN 900, (SCALED PIPE)| polyethylene pipe production, DN 200, SDR 41 | Cut-off, U	*1 m of polyethylene pipeline*	*(Nemecek et al., 2007)*
	Water treatement {GLO}| tap water production, seawater reverse osmosis, conventional pretreatment, enhance module, two stages | Cut-off, U	*1 kg of freshwater*	*(Open University & Bearman, 1989)*
	Freshwater pump, for industrial applications (Scaled) {GLO}| water pump production, 22kW | Cut-off, U	*1 unit of freshwater pump*	*(Nemecek et al., 2007)*

Copper beneficiation plant

The copper beneficiation plant consists of the "Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore" dataset from the Ecoinvent database within SimaPro software (Appendix A Table 7 and Appendix B Table 10). This dataset is specific to the mining and beneficiation of copper sulfide ores in Chile, a region known for its significant copper production. The dataset accounts for the entire copper production process, from mining and ore beneficiation to the production of copper sulfide concentrate.

System boundaries for the copper beneficiation plant include all activities from the construction of the mine site to the closure and deconstruction of the site (Figure 11). This comprehensive scope ensures that the environmental impacts associated with copper production are thoroughly captured. The technological framework is based on current mining practices in Chile, including open-pit and underground mining methods, flotation processes, and the management of overburden materials and sulfidic tailings. In the Chilean context, copper mining is conducted 70% through open-pit methods and 30% through underground operations. The beneficiation process involves the flotation of copper and molybdenite, during which significant amounts of chemical agents are introduced. Overburden materials are disposed of separately from sulfidic tailings near the mining site. It is important to note that the dataset does not include the dewatering or other pre-treatment processes of tailings, as these activities are considered site-specific and are modelled separately (Classen et al., 2009; Northey et al., 2014; Turner & Hischier, 2020).

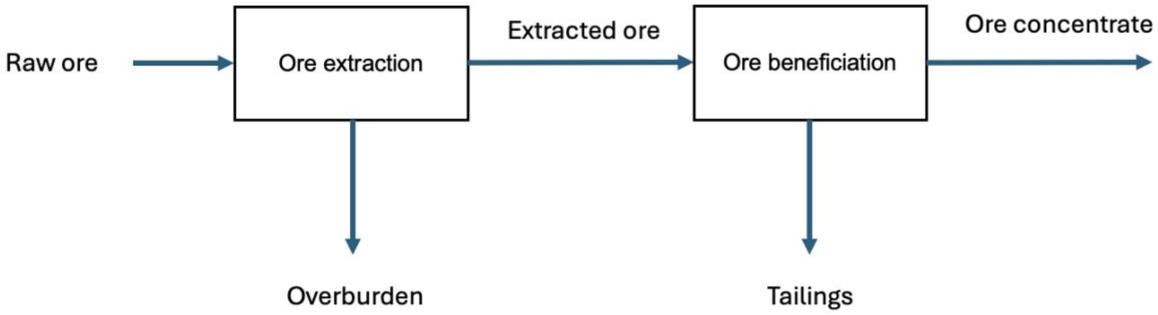

Figure 11: System boundaries of the base case (Copper mine operation and beneficiation, sulphide ore (CL) (Ecoinvent).

Key input parameters, such as ore grades, production volumes, and beneficiation efficiency, have been revised to ensure temporal and geographical representativeness. The estimated average copper ore grade in Chile is now reported as 0.6% (Codelco, 2024). This update enhances the accuracy and relevance of the dataset for contemporary analyses.

There are different types of inputs and outputs, such as inputs in nature with multiple sub-compartments: in-ground, land, air, biotic, and water. Inputs from the technosphere include materials and fuels or electricity and heat. This dataset also considers the emissions to air, giving the amount in kg and some details of low or high population density. Ecoinvent provides detailed information on water emissions in kilograms, specifying the affected water bodies such as rivers, oceans, and groundwater, as well as whether they constitute long-term pollution. Emissions to soil are gathered, and its amount is also expressed in kg. The sub-compartment can be agricultural, industrial, or forestry. Lastly, final waste flows, non-material emissions, social issues, economic issues and outputs to Technosphere: waste treatment (Classen et al., 2009; Northey et al., 2014; Turner & Hischier, 2020).

The amount of reagents needed is significantly influenced by the type of treated minerals. As each mineral is unique, the required doses can differ between plants and may even change daily. Moreover, companies frequently switch reagents based on the supplier. In numerous instances, combinations of chemicals with exclusive formulas are utilised. A sensitivity analysis targeting the specific chemicals was done, and no changes in the single score were spotted, which means that the reagents are not a decisive parameter regarding impact categories.

In Scenario 1, where seawater is used in the copper beneficiation process, specific chemicals are applied in precise amounts to optimise flotation. The primary collector is xanthate, dosed at 22.5 grams per ton (gpt). 4-Methyl-2-pentanol is the primary frother, applied at five gpt to stabilise the froth. Sodium metabisulfite serves as a depressant. This chemical was not available in Simapro, so it was substituted by disodium disulphite, which has the same CAS number. It was used at 162 gpt to reduce the floatability of unwanted minerals. For raw seawater, the pH regulator used is sodium metabisulfite, which is particularly effective in achieving the required pH levels of 10 to 11 due to its ability to counteract the high magnesium content. Sodium metabisulfite acts as a depressant by converting pyrite into a hydrophilic form, causing it to precipitate and thus preventing it from floating (Suyantara et al., 2023). Additionally, polyacrylamide is used as a flocculant, dosed at 15 gpt based on dry tailings, to aid in solid-liquid separation during the tailings management process.

Scenario 2 also includes the database of scenario 1 named “Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore" from the Ecoinvent database. Using desalinated water, several reagents are employed to optimise mineral separation in the flotation process. The effective separation of minerals relies heavily on using various chemical reagents, each playing a particular role in enhancing the efficiency of the operation. Collectors are critical as they induce hydrophobicity in mineral particles, making them more likely to attach to air bubbles and float to the surface; potassium xanthate is the most used (Ackerman et al., 1987). The primary collector, Isopropyl Xanthate, substituted in SimaPro for a chemical with the same CAS number named Sodium ethyl xanthate dosed at 22.5 gpt of mineral. For frothing, Palm Oil is used as the primary frother at a concentration of 16 gpt of mineral. Foaming agents increase the contact area between bubbles and particles, stabilise the foam, and reduce the induction time for particle-bubble adhesion, thereby improving the overall froth quality (Ramos et al., 2013). Modifiers, including activators, depressants, and pH regulators, are used to control the physico-chemical conditions of the flotation system and to properly optimise the environment. These reagents alter pH values, activate the floatability of some minerals, and depress others selectively to enhance the efficiency of separation. In Scenario 2, the pH regulator used is Lime (CaO); for systems using desalinated seawater, which lacks significant magnesium, lime is the preferred pH regulator. Lime efficiently adjusts pH levels without the need for additional depressants, facilitating optimal flotation conditions and improving the overall efficiency of the mineral separation process (Suyantara et al., 2023). Lime is applied as a depressant at a rate of 4 kilograms per ton (kgpt) of mineral, helping to control pH and prevent unwanted mineral flotation. In the thickening phase, Polyacrylamide is utilised as a flocculant at 12.75 gpt of dry tailings to aggregate fine particles, improving the efficiency of solid-liquid separation. This carefully selected combination of reagents is essential for achieving optimal mineral processing outcomes. All the reagents were added to the software SimaPro according to the functional unit of 1 ton of copper concentrate.

Pipelines and pumping stations

Given the large distances between Chilean copper mining activities and the coast, due to the common geographic challenges faced by Chilean mining operations, the involvement of seawater, in general, requires significant energy for transportation. In this study, a distance of 170km between the coast and the mining activities is assumed (Vargas et al., 2023).

Three pipelines, each with a diameter of 36 inches (around 900mm) and an equal length of 56.6km, are required to transport the seawater from the coast to the mine. The pipeline utilised in both situations is constructed from high-density polyethene (HDPE), which was selected for its extensive use in transporting both seawater and freshwater. HDPE pipelines are preferred in industrial settings because of their resistance to corrosion, flexibility, and assumed 75-year service life, as stated in this study. The selection of HDPE is also backed up by recommendations from industry guidelines, including those from the manufacturer Simona AG, which affirm its appropriateness for utilisation in seawater desalination and distribution systems (*Simona AG*, 2018).

In order to accommodate the requirements of the LCA study, the existing HDPE pipeline data was sourced from the Ecoinvent database, representing a pipeline with a nominal diameter of 200mm and a wall thickness of 5mm (Nemecek et al., 2007). The pipeline was scaled up to a larger pipeline with a nominal diameter of 900mm and an average wall thickness of 53mm. This adjustment involved scaling the material input per meter of the pipeline by scaling both the diameter and wall thickness. Real-life HDPE pipeline products for water supply from the manufacturer *High Mountain* were referenced to ensure accurate and realistic scaling of the material. Consequently, the amount of input material, as well as the associated outputs and waste, were adjusted proportionally to reflect the new dimensions of the pipeline (Appendix A Tables 8 and 9, Appendix B Tables 12 and 13).

In the process of transporting seawater from coastal areas to copper mining operations, pumping stations are essential to maintain a consistent flow along the pipeline. For this study, three pump stations are positioned along the pipeline to maintain a constant water flow rate of 4,938m^3/h, indicating the high water needs often seen in copper mining activities (Vargas et al., 2023). For the two scenarios analysed in this study, the transportation of raw seawater and the transportation of desalinated water both require different materials for manufacturing the pumping stations because of the differing corrosive characteristics of the water.

In the first scenario, where raw seawater is transported directly to the mine, the pumping stations are manufactured from highly corrosion-resistant materials to withstand the harsh conditions imposed by saltwater. Therefore, Stainless steel and copper bronze are used in manufacturing the pumps and related infrastructure because they have better corrosion resistance in marine environments. On the other hand, the second scenario, which includes the transferring of desalinated water, poses a significantly reduced chance of corrosion. With high concentrations of calcium carbonate ($CaCo_3$) and gypsum ($CaSO_4$), in addition to sodium chloride (NaCl), seawater is significantly more corrosive than freshwater (Sotoodeh, 2022). Consequently, typical materials, including cast iron and carbon steel, are employed in the manufacturing of the pumps, as they are commonly used in environments with lower corrosive capabilities. The variances in material choice in the two situations highlight the importance of considering water characteristics in the design and construction of infrastructure for water transfer in mining operations.

It is crucial to scale pump data from the Ecoinvent database to accurately estimate energy and material inputs for seawater and desalinated water pumping systems. The data in Ecoinvent provides details on a 22 kW pump used for transporting freshwater, which is manufactured from cast iron and carbon steel (Nemecek et al., 2007). The pumping energy needed to move water through the HDPE pipeline was determined by considering the frictional head loss along the 170km route (Vargas et al., 2023). After considering the hydraulic features of the pipeline, the water flow rate, and the friction-induced energy losses, the pumping power was calculated based on a pipe diameter of 900mm. It is estimated that the pumps have an average lifetime of 15 years, operating for a total of 100,000 hours due to the high demands of long-distance water transport systems. For this study, three pumping stations needed pumps with a power of 2MW each. The scaling of the pumps is performed by comparing the weight of commercial water pumps with similar power ratings, particularly those manufactured by OMEC Motors, to keep the material input consistent with the products in reality.

For the desalinated water transportation scenario, the materials currently in the Ecoinvent model, such as cast iron and carbon steel, were adjusted based on the weight of the 2 MW pumps. Nevertheless, the corrosive nature of saltwater in the seawater situation required a change in the materials being used. Copper bronze and stainless steel replaced cast iron and carbon steel due to their corrosion resistance in marine conditions. This change in material was also adjusted in proportion to the weight of the pumps to accurately depict the actual conditions of the pump system in the seawater environment.

Desalination plant

The desalination process starts with seawater intake, where the process “Water treatment {GLO}| tap water production, seawater reverse osmosis, conventional pretreatment, enhance module, two stages | Cut-off, U” from the Ecoinvent database was used and modified to reflect the specific case study conditions as illustrated in Appendix B Table 10. According to Minera Spence S.A., (2015), 2.5m³ of seawater is needed to produce one m³ of desalinated water (Blanco et al., 2018). In SimaPro, this intake flow was modelled to match this ratio of seawater input to freshwater output. The environmental impacts associated with the withdrawal of seawater were also incorporated within the system boundaries (Open University & Bearman, 1989).

Once the seawater enters the plant, it undergoes pretreatment to remove large debris and particles, preparing the water for desalination. This step includes processes like chlorination, coagulation, flocculation, and filtration. In SimaPro, this phase was modelled by adding specific material inputs, such as sodium hypochlorite for chlorination and sulfuric acid to adjust pH levels, enhancing the removal of solids. The Ecoinvent dataset was modified to accurately represent the amount of these chemicals used in pretreatment; see Appendix B Table 10 for more details.

Following pretreatment, the core desalination process uses a two-stage enhanced membrane system in the reverse osmosis unit. High pressure is applied to separate fresh water from concentrated brine. In SimaPro, this step was modelled using the reverse osmosis process from the Ecoinvent database, adjusted to account for local conditions, such as the energy profile in Chile. Energy consumption during this phase is significant, but the incorporation of energy recovery systems helps reduce overall energy usage. While the original Ecoinvent process is based on a global geographical scope, adjustments were made to align the electricity consumption with Chile’s local energy market. These modifications are important for capturing the true environmental impact of the desalination plant, as Chile's energy mix affects the overall carbon footprint of the process (Open University & Bearman, 1989). In addition to energy, various chemicals are required to maintain and optimise the desalination process. These include sodium meta-bisulphite substituted by disodium disulfite, citric acid, sodium hydroxide, and anti-scalants, all of which were incorporated into the SimaPro model as specific input flows. The quantities of these reagents were based on the specifications of the case study Minera Spence S.A., (2015), ensuring an accurate representation of the desalination plant’s operations.

Additionally, lime should be included as a depressant to be able to create a pH change in scenario 2 desalinated seawater, aiming to achieve a pH level of 10-11. Adding lime causes a transformation where pyrite no longer floats, becoming hydrophilic and precipitating when wet. Carbon dioxide is included as a stabiliser, and a corrosion inhibitor is also added to the desalinated water to prevent high corrosiveness. Sodium hypochlorite will be included to manage the growth of microbes within the system (Minera Spence S.A., 2015),.

After reverse osmosis, the freshwater produced undergoes post-treatment, including re-carbonation, to meet the required quality standards. In SimaPro, the post-treatment was modelled by adjusting the water output flow to account for this final step, incorporating necessary material inputs to ensure the water meets the required specifications. The by-product of the reverse osmosis process is brine, which is discharged back into the sea. The environmental impact of this brine discharge, particularly its potential effects on marine ecosystems, was modelled in SimaPro by including brine as an output flow and assigning it an environmental impact factor based on the local conditions of the discharge.

4.3 Impact Assessment: LCIA

The procedure involves adding the inventory list into the software, selecting the preferred LCIA method, and allowing the software to carry out the calculations. This section, the Life Cycle Impact Assessment (LCIA), focuses on the environmentally relevant impacts associated with the two case studies. According to ISO (2006), LCIA can be subdivided into five essential steps:

i) **Selection and Identification of Impact Categories**: Selecting the applicable environmental effect categories for the filter tailings and paste thickening methods.

ii) **Classification**: Assigning the relevant impact categories to inventory data.

i) **Characterisation**: Measuring how much each inventory item contributes to the effect categories.

ii) **Characterisation**: In order to assess the extent of impact a product or service has in each impact category, every substance is multiplied by a factor that represents its relative contribution to the environmental impact.

iii) **Damage assessment**: This optional phase describes, in a more aggregated way, how various impact categories contribute to the endpoint impact (Damage) categories of the chosen impact assessment technique.

iv) **Normalisation**: The results are compared to a reference value in this optional stage, such as the typical annual environmental effect made by one person.

v) **Weighting**: The normalised indicators of each effect category are multiplied by a weighting factor in this optional step. Impact categories that are considered more "important" are associated with higher weighting factors. There is just one score that can be obtained by adding the weighted outcomes, which all have the same unit.

vi) **Single score:** The weighted results are combined in this stage to get a single score that represents the total environmental impact.

LCIA provides crucial information to understand the magnitude, extent and localised or widespread nature of these impacts. It involves the input of an inventory list in the software, selecting the preferred LCIA method, which will be the Environmental Footprint 3.1 (EF 3.1) (adapted) [version 1.00] for application, letting the software do the calculations.

The EF 3.1 [version 1.00] method, adapted for SimaPro method, was chosen to carry out the LCIA of both scenarios. The European Commission developed this method as part of the Single Market for Green Products Initiative, which aims to standardise environmental performance assessments across the EU and support the use of product environmental footprint category rules (PEFCR) as well as organisation environmental footprint sector rules (OEFSR) (European Commission: Joint Research Centre et al., 2022). The EF 3.1 method is utilised in this study due to its suitability for non-EF 3.1 libraries, such as Ecoinvent, which is the one used in this dissertation. This adaptation is designed to address the potential under-characterisation of regions and sub-compartments present in non-EF libraries with the aim of maintaining LCA results that are highly accurate and representative when datasets outside the EF 3.1 database are used. In addition, this version was specifically tailored to better accommodate the substances used in the SimaPro data libraries, including additional flows commonly found in background databases, as well as the removal of certain flows and sub-compartments unfamiliar to SimaPro. Regarding synonymous or duplicate EF substances, singular substances have been added to streamline the method and achieve a higher level of consistency (Donaldson & PRé, 2023).

Table 4: *Impact categories of EF 3.1 (adapted) method in SimaPro.*

	IMPACT CATEGORY	UNIT
1	Resource use, minerals and metals	kg Sb eq
2	Eutrophication, freshwater	kg P eq
3	Human toxicity, non-cancer	CTUh
4	Particulate matter	disease inc.
5	Ecotoxicity, freshwater - part 1	CTUe
6	Human toxicity, cancer	CTUh
7	Resource use, fossils	MJ
8	Acidification	mol H+ eq
9	Photochemical ozone formation	kg NMVOC eq
10	Eutrophication, terrestrial	mol N eq
11	Climate change	kg CO2 eq
12	Ecotoxicity, freshwater - part 2	CTUe
13	Eutrophication, marine	kg N eq
14	Ozone depletion	kg CFC11 eq
15	Water use	m3 depriv.
16	Land use	Pt
17	Ionising radiation	kBq U-235 eq

This version of EF 3.1 offers a solid, empirically supported framework for SimaPro environmental impact studies. The methodological integrity and practical application are carefully balanced to enable users to do comprehensive assessments with data and processes that are compatible with their current databases. The method's reliability and usefulness in assessing a variety of environmental consequences across sectors are further enhanced by its foundation in reputable scientific literature and European Commission directives.

4.4 Interpretation

The final step involves the interpretation of the results from the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) for both case studies. This phase aims to identify key hotspots in both approaches, allowing for the formulation of conclusions and recommendations that can guide decision-making and improve environmental performance. A comparison between Case 1 and Case 2 will also be developed to highlight their differences and similarities.

Both scenarios are first evaluated using SimaPro software and the EF 3.1 method to get the values of each impact category. A Pareto analysis will be conducted to identify the most significant impact categories and processes that contribute to relevant environmental effects after normalising and weighting the values. The responsible processes for each impact category are then identified using SimaPro's "Processes" function, which allows for a clear visualisation of flow networks and facilitates an understanding of their contributions. The output substances related to these impacts are also defined within SimaPro and further analysed to determine their sources. Further analysis such as single score, relative deviation and sensitivity analysis were done to complement the previous analysis. Finally, recommendations are provided to reduce or mitigate the output of these substances.

5. Results and Discussion

This part offers an analysis and discussion regarding the findings of this dissertation. First, the comparison between the two scenarios is conducted (section 5.1), and then the hotspots of each scenario are analysed by identifying their environmental impacts (sections 5.2 and 5.3).

5.1 Comparison of Scenario 1 and 2

This section compares the two scenarios, with the results interpreted and discussed using the EF 3.1 method in SimaPro. The analysis in Table 5 shows that Scenario 2 consistently results in higher environmental impacts across all categories compared to Scenario 1. The table provides an analysis of different environmental impact categories, displaying the characterised values for both scenarios and highlighting their deviations. Each category is represented with specific units of measurement, showing significant differences between the two scenarios.

Table 5: Comparative table with characterised values from Scenario 1 and 2 of each impact category and the deviation.

Impact category	***Unit***	***Scenario 1***	***Scenario 2***	***Deviation***
Acidification	mol H+ eq	27.3	62.3	-56%
Climate change	kg CO2 eq	1216.9	6227.9	-80%
Climate change - Biogenic	kg CO2 eq	1.7	12.3	-85%
Climate change - Fossil	kg CO2 eq	1214.3	6212.2	-80%
Climate change - Land use and LU change	kg CO2 eq	0.7	3.4	-78%
Ecotoxicity, freshwater - part 1	CTUe	17578.5	94164	-81%
Ecotoxicity, freshwater - part 2	CTUe	38130.8	43927.1	-13%
Ecotoxicity, freshwater - inorganics	CTUe	55293.5	134144.2	-59%
Ecotoxicity, freshwater - organics - p.1	CTUe	257.9	2052.4	-87%
Ecotoxicity, freshwater - organics - p.2	CTUe	157.9	1894.5	-92%
Particulate matter	disease inc.	0.0002	0.0009	-78%
Eutrophication, marine	kg N eq	7.6	14.2	-46%
Eutrophication, freshwater	kg P eq	11.2	12.8	-12%
Eutrophication, terrestrial	mol N eq	113.4	174.7	-35%
Human toxicity, cancer	CTUh	2.01E-06	2.02E-05	-90%
Human toxicity, cancer - inorganics	CTUh	1.57E-06	3.80E-06	-59%
Human toxicity, cancer - organics	CTUh	4.43E-07	1.64E-05	-97%
Human toxicity, non-cancer	CTUh	0.0002	0.0003	-30%
Human toxicity, non-cancer - inorganics	CTUh	2.79E-05	0.0001	-77%
Human toxicity, non-cancer - organics	CTUh	0.0001	0.0002	-2%
Ionising radiation	kBq U-235 eq	27.2	67.7	-60%
Land use	Pt	81794.7	89916.6	-9%
Ozone depletion	kg CFC11 eq	2.02E-05	0.01	-100%
Photochemical ozone formation	kg NMVOC eq	22.0	40.7	-46%
Resource use, fossils	MJ	13950.5	74516.7	-81%
Resource use, minerals and metals	kg Sb eq	3.5	3.5	-1%
Water use	m3 depriv.	242.7	1976.2	-88%

The most significant differences are observed in the categories of *Climate Change, Freshwater Ecotoxicity,* and *Fossil Resource Use*, where Scenario 2 demonstrates much higher impacts. For instance, the *Climate Change* category, in terms of biogenic and fossil-related emissions, shows a high contrast, indicating that desalinated water in Scenario 2 is considerably more energy-intensive, contributing to higher greenhouse gas emissions. *Acidification*, *Eutrophication*, and *Particulate matter* also show substantial deviations, highlighting the increased environmental burden associated with Scenario 2. These results suggest that the processes involved in desalination, particularly energy consumption and chemical use, contribute significantly to these impact categories.

Notably, certain categories, like *Water Use*, show a significant difference between the two scenarios, highlighting the resource-intensive characteristics of desalinated water. On the other hand, categories such as *Mineral and Metal Resource Use* display insignificant variations, suggesting that the selection of water sources does not greatly influence certain effects. The comparison in Table 5 reinforces that scenario 2 poses a significantly higher environmental challenge, particularly in energy-related and toxicity categories, which suggests the need for further exploration of more sustainable desalination technologies to mitigate these impacts.

The relative deviation of both scenarios was calculated using the single score (SS):

$$Relative\ deviation = \frac{SS2 - SS1}{SS1} \quad \text{Eq. 1}$$

The relative deviation of both scenarios was calculated with the single scores. The relative deviation between scenario 1 and scenario 2 is approximately 12.5% (Figure 17). This percentage represents how much Scenario 2's environmental impact differs from Scenario 1's impact relative to Scenario 1's value. The single score is very useful for comparing two LCA results providing the comparison of environmental impacts. The single score for scenario 1 was determined by summing the weighted environmental impact values, resulting in a total of 4,63 for 1 t of copper concentrate. Then, in scenario 2, the environmental impact value was calculated to be 5,21 for 1 t of copper concentrate.

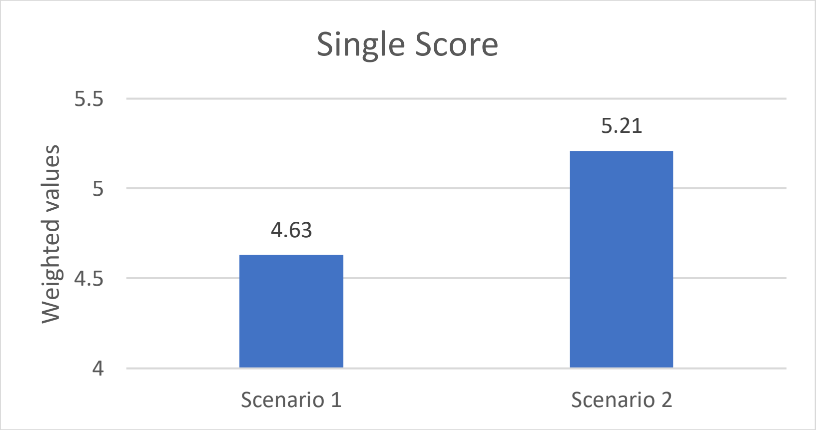

Figure 12: Single score comparison between Scenario 1 and 2.

5.2 Hotspots of Scenario 1: Seawater use

The environmental impacts of scenario 1, which utilises seawater as the source for the copper concentration plant, will be presented. The results will be interpreted and discussed using the EF 3.1 method and Pareto's diagram.

Figure 12 presents a Pareto diagram with the results of Scenario 1 after applying the EF 3.1 method. The x-axis represents various environmental impact categories, such as *Eutrophication, freshwater use*, and Climate Change, while the left y-axis indicates the magnitude of their contributions. The Pareto diagram illustrates the relative importance of each factor in the total impact, highlighting the most significant impact categories. The blue bars represent the weighted values for each category, and the orange line indicates the cumulative percentage. The findings reveal *that Resource use, minerals, and metals* account for more than 90.5% of the overall environmental impact in this scenario. According to Pareto's 80/20 principle, which suggests that approximately 80% of effects come from 20% of cases, this high concentration of impact in the *Resource use, minerals, and metals* category is significant. The orange line's starting point at 90.5% on the right y-axis underscores the dominant role of this category. This cumulative percentage line starts high and increases gradually, indicating that focusing on improving environmental performance in *Resource use, minerals, and metals* would result in the greatest reduction in the overall environmental footprint of the analysed value chain. This substantial impact is consistent with the nature of scenario 1, which involves a copper concentration plant, where copper mining plays a critical role due to its dependence on accessing underground ore deposits, two energy-intense processes (Classen et al., 2009; Northey et al., 2014; Turner & Hischier, 2020).

Furthermore, *Eutrophication, freshwater* emerges as the second most significant impact category, contributing 4.24% to the total environmental impact, though its contribution is considerably smaller than the leading category. Other categories, such as *Climate change* and *Particulate matter*, contribute minimally, accounting for 0.73% and 0.7% of the total impact, respectively. Additional impact categories, including *Photochemical ozone formation, Acidification,* and others, have an even lower influence, with their contributions being almost negligible when compared to the top three categories. These categories are barely noticeable in the diagram.

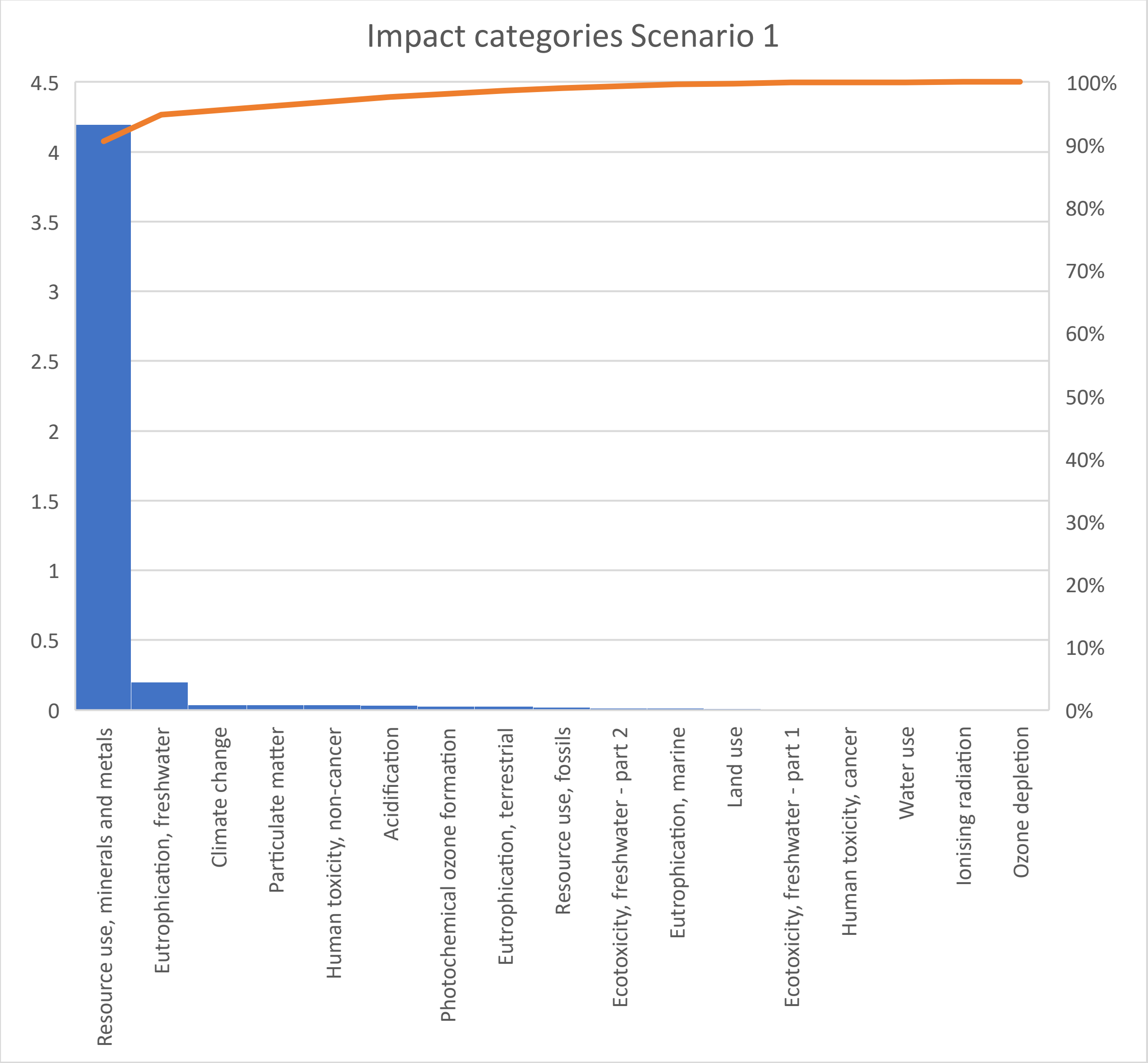

Figure 13: Pareto analysis of weighted values of scenario 1, the copper beneficiation plant with seawater as a source of water using the EF 3.1 method.

The next step in analysing the results is to break down the environmental impacts and identify the processes contributing the most to the critical impact categories. This analysis were performed by examining the network displayed in SimaPro, as shown in Figure 13 and applying a cut-off percentage to gain a comprehensive understanding of the contributing processes. For *Resource use, minerals and metals* in scenario 1, the copper beneficiation plant, specifically the process titled "Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore", is the primary source of this impact (Figure 13) contribuiting the 99,28% and the remaining processes only a 0,72%. The remaining processes are the “Seawater pump, for industrial applications (Scaled) {GLO}| water pump production, 22kW | Cut-off, U” and the “HDPE pipe, DN 900, (SCALED PIPE)| polyethylene pipe production, DN 200, SDR 41 | Cut-off, U”.

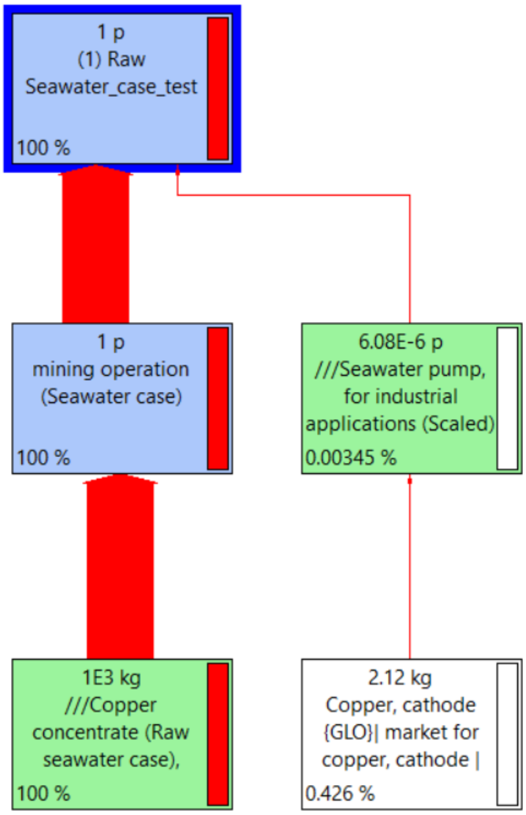

Figure 14: Network of the processes contributing to *Resource use, minerals and metals* and cut-off 0.85%.

In order to have higher level of detail, the output substances of the main activity were identified. The substances in the "Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore" are primarily composed of tellurium (Te), accounting for 76%, followed by copper at 11%, and selenium at 4%, with the remaining 9% consisting of other elements (Figure 14).

The reason for the high amount of Te found in copper mining is that it is often linked with copper ores. Te is frequently a secondary product of copper mining, especially in areas where Te is naturally found in the ore. Due to the extraction of significant amounts of material during copper mining, it is unavoidable to find Te. During open-pit mining, a large amount of ore is handled, leading to a higher chance of extracting unwanted materials such as Te. Bringing up optimising statistical models to decrease gangue extraction underscores the significance of reducing the environmental impact of non-target materials such as Te. Furthermore, the impact of Te on the *Resource use, minerals and metals* category could be substantial due to its rarity and rising demand in sectors such as solar energy and electronics (Bustamante & Gaustad, 2014). In conclusion, the abundance of Te may be attributed to its existence in copper ores and the operations of extensive open-pit mining that handles significant quantities of material.

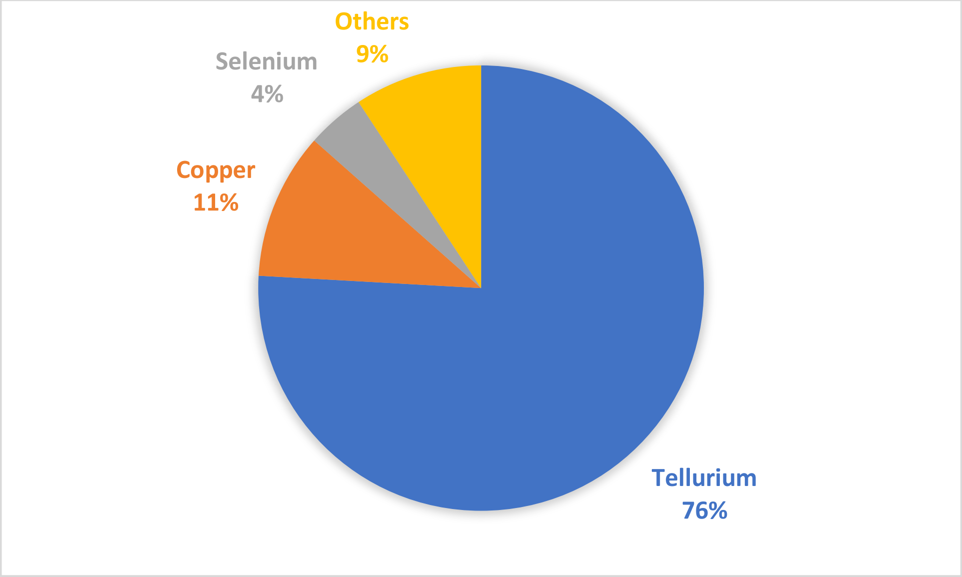

Figure 15: Pie chart of the main substances related to the process mining operation, the highest contributor to the imact category *Resource use, minerals and metals* in scenario 1.

The resource use, minerals and metals category emerge as the most significant impact category for scenario 1, as demonstrated by the Pareto analysis. In this instance, it accounts for over 80% of the total environmental impact. This means that, in scenario 1, the resource use, minerals and metals category contribute most of the environmental burden, while the other impact categories play a much smaller role.

Given its dominant contribution, focusing on reducing this category's impact would lead to the most substantial decrease in the overall environmental footprint. This large percentage also emphasises the relatively minor role of other categories, such as *Eutrophication, freshwater*, and climate change. As a result, the resource use, minerals and metals category become the most relevant area of focus for this scenario.

5.3 Hotspots of Scenario 2: Desalinated water use

Scenario 2 evaluates the environmental impacts associated with using desalinated water in the copper concentration plant. The same procedure as with scenario 1 will be followed, first, the results will be displayed in a Pareto's diagram illustrating the distribution of these impacts across the relevant impact categories (Figure 15). This will be followed by a network flow analysis of the impact categories with the highest values, identifying the processes involved. Finally, the substances released by the primary process contributing to the analysed impact category will be examined.

Figure 15 indicates that the main factor contributing to the environmental impact is *Resource use, minerals and metals*, corresponding to 81,12%, mirroring scenario 1. In the category *Eutrophication, freshwater* is the second most important impact category, despite making a smaller contribution of 4,3%. This is followed by *Climate change* accounting for 3,33%, *Particulate matter* at 2,87%, and *Resource use, fossils* showing 1,8%. Other impact categories such as *Acidification, Photochemical ozone* *formation,* and *Human toxicity, non-cancer* make only a small contribution, as shown by their tiny bar sizes. Their impact on the overall environmental profile is minimal.

The overall environmental impacts are primarily driven by a few key categories, as suggested by the cumulative curve similar to scenario 1. The biggest impacts are from *Resource use, minerals and metals* and *Eutrophication, freshwater*, whereas other sectors have minimal influence. This implies that despite the transition to desalinated water, the main environmental impact continues to come from the extraction of resources linked to the process of concentrating copper.

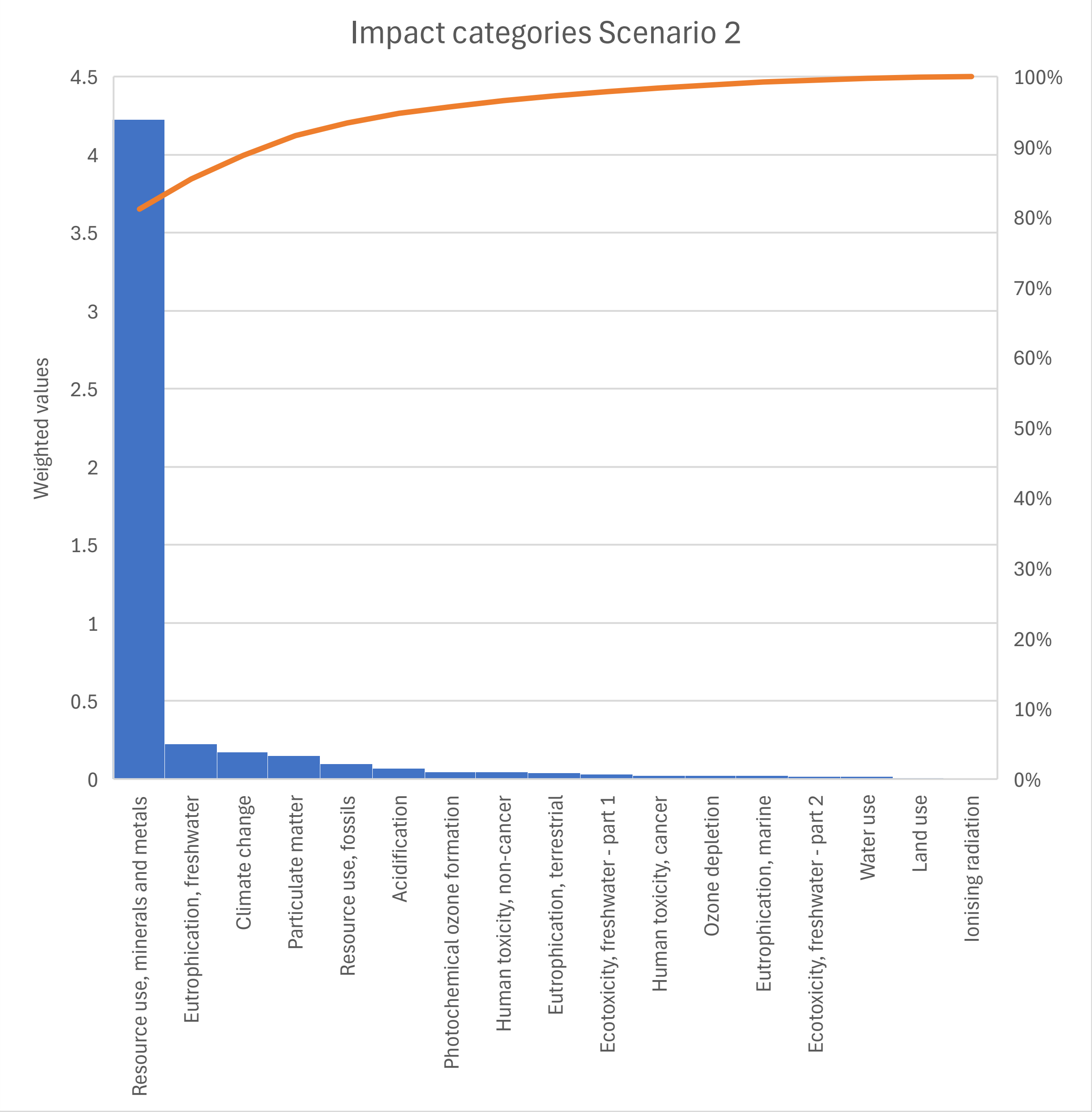

Figure 16: Pareto analysis of the weighted values of scenario 2, copper beneficiation plant with desalinated water as a source of water using the EF 3.1 method.

The impact category *Resource use, minerals and metals* is represented in Figure 16 with a cut-off value of 0.85%, this category has as a process source the "Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore". The process is contributing 99,2% to the impact category previously mentioned, only a 0,8% is related to the desalinated plant.

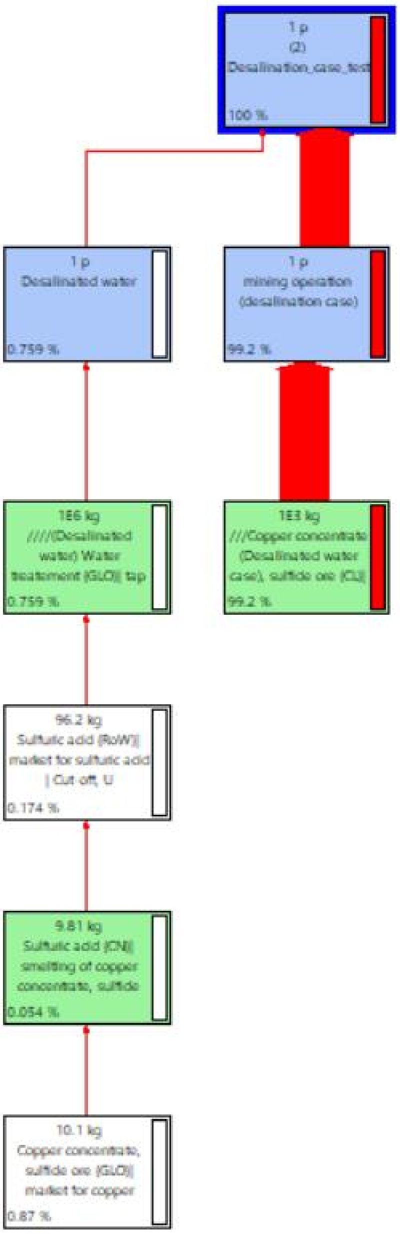

Figure 17: Network visualisation of the impact category *Resource use, minerals and metals* with a cut-off value of 0.85% % in scenario 2.

In scenario 2, the output substances from the copper concentration process remain the same in elemental composition as scenario 1, with Te (76%) being the most abundant, with copper (11%) and selenium (4%) following closely behind, as illustrated in Figure 14. Nevertheless, the utilisation of desalinated water in this situation leads to added environmental consequences reflected in higher values than scenario 1 in the Pareto analysis (Figure 15), mainly because of the increased energy requirements of the desalination process. Despite this, the category *Resource use, minerals, and metals* remain the primary factor influencing impact, mostly due to the abundance of Te. This emphasises the constant need to improve processes to minimise the extraction of unwanted elements like Te, especially with the increasing demand for rare elements in industries like electronics and renewable energy.

In scenario 2, the resource use, minerals and metals category similarly emerge as the dominant impact category, contributing 81.12% of the total environmental impact, as shown by the Pareto analysis. In this case, *Resource use, minerals and metals* stand as the most significant contributors, while the other categories, including *Eutrophication, freshwater* and climate change, have minimal influence. This large percentage suggests that targeting improvements in the resource use, minerals and metals category would lead to the greatest reduction in environmental impact for scenario 2. Like in scenario 1, the other impact categories make such a small contribution that their overall influence is relatively insignificant. Therefore, it becomes clear that the resource use, minerals and metals category is again the key focus in this scenario, largely driven by the copper concentration process.

5.4 Environmental impacts for water management

To gain a clearer understanding of the environmental impacts associated to water management in the copper concentration process, it has been decided to perform a separate analysis that intentionally excludes the copper concentration process from both scenario 1 (seawater) and scenario 2 (desalinated water). This adjustment was made because the copper concentration process significantly dominates the *Resource use, minerals, and metals* category, contributing over 80% of the total environmental impact in both scenarios. By excluding this process, we can focus on the specific contributions of seawater and desalinated water to environmental impacts that might otherwise be masked.

The objective of this section is to clarify the environmental implications of water management practices in copper mining. By analysing only the water systems, it is possible to discern how each water source affects various environmental categories. This approach helps to understand how different water management strategies influence the overall environmental footprint of copper mining operations, allowing for a more detailed comparison between seawater and desalinated water use.

The results of this analysis reveal notable differences in primary impact categories between scenario 1 and scenario 2. For instance, as depicted in Figure 25, *Resource use, fossil fuels* appear as the most significant impact category in scenario 1. However, Figure 26 shows that scenario 2 has a different impact category in the first place; the most significant is *Climate change.*

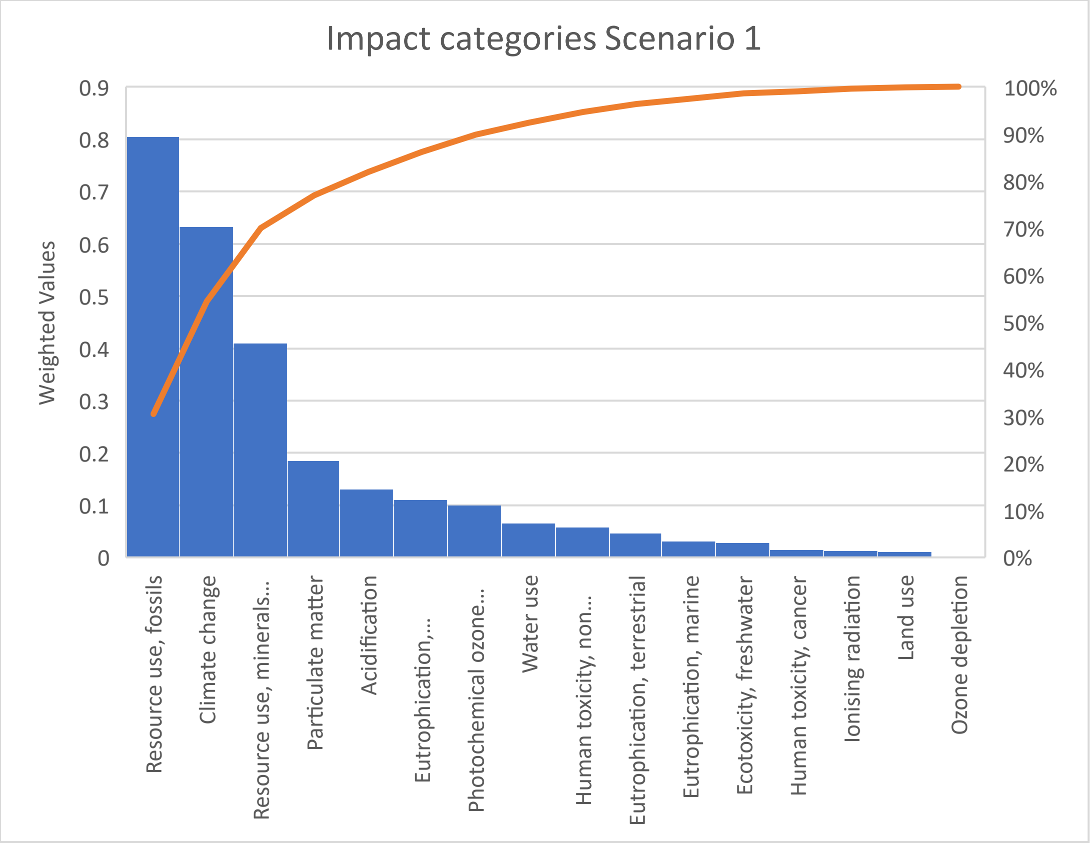

Figure 18: Pareto analysis of scenario 1 impact categories using the EF 3.1 method.

In scenario 1, the main factor contributing to *Resource use, fossils* being the most impactful category is the process "HDPE pipe, DN 900, (SCALED PIPE)| polyethylene pipe production, DN 200, SDR 41 | Cut-off, U" accounting for a 64.5%, the other 35.4% is related to the "Seawater pump, for industrial applications (Scaled) {GLO}| water pump production, 22kW | Cut-off, U".

The building and maintenance of the pipeline system also worsen the depletion of fossil fuels. Substances like high-density polyethylene (HDPE) that are utilised in pipelines are derived from fossil fuels. The high resource use in this situation is driven by the total energy needs for running the pumps, creating electricity (often from power plants that use fossil fuels), and manufacturing infrastructure materials. The pie chart illustrates the output substances from the high-density polyethene (HDPE) pipeline process in scenario 1. *Oil, crude* dominates the emissions at 54%, followed by *Gas, natural* at 30%, highlighting the fossil fuel-intensive nature of the pipeline construction and operation. "*Coal, hard"* contributes 10%, while *Uranium* makes up 5% and "*Coal, brown"* 1%. Other substances account for 0.8%. These emissions emphasise the substantial reliance on fossil fuels for producing HDPE pipes and powering the pumping systems, particularly as the energy demands for moving seawater uphill in a complex pipeline system are significant. The construction of the pipeline system, along with the maintenance and energy consumption for seawater transport, intensifies the depletion of fossil fuel resources, leading to high impacts in the *Resource use, fossils* category in scenario 1. The dependence on fossil fuels for energy generation, as well as the use of materials derived from fossil resources, is a key factor in this scenario's environmental footprint.

Furthermore, substantial energy requirements for moving seawater to the copper processing facility. Because the plant is situated at a high altitude and takes in seawater from the ocean, a complex network of pipelines and pumping stations is needed to move the water uphill. This procedure uses a significant quantity of energy, mostly obtained from fossil fuels, to constantly power the pumps that transport water over extensive distances and uphill. Therefore, the main factors causing high *Resource use, fossils* in scenario 1 are the dependence on energy-intensive procedures, consumption of fossil fuels for generating electricity, and use of materials derived from fossils in constructing infrastructure.

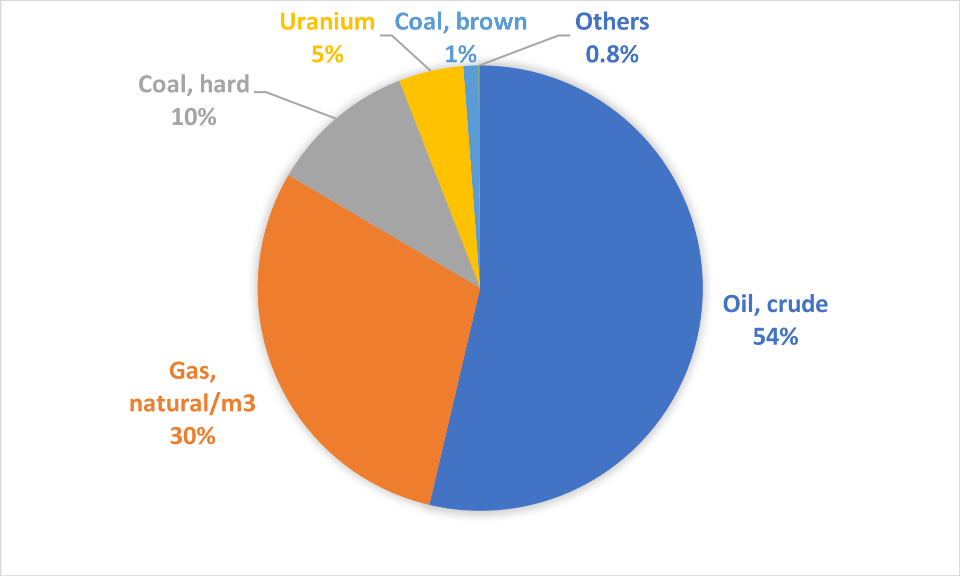

Figure 19: Piechart of the output substances of the process HDPE pipeline in scenario 1.

In scenario 2, the primary influence on *Climate change* arises from the energy-heavy desalination process covering a 99%. Seawater undergoes treatment in a desalination facility with reverse osmosis technology to create freshwater appropriate for mining activities. This procedure necessitates large quantities of electricity, a significant portion of which typically comes from fossil fuels. The use of fossil fuels for energy leads to the emission of greenhouse gases like CO_2 and CH_4, responsible of global warming. The desalination plant's high energy usage and the manufacturing and delivery of necessary chemicals greatly raise the system's carbon emissions. Additionally, the energy demand of the infrastructure, such as pipelines and pumping stations, contributes to the overall impact of *Climate change*. Therefore, the main reason for the increased *Climate change* impact in scenario 2 is the heavy dependence on fossil fuels for the desalination plant and its infrastructure.

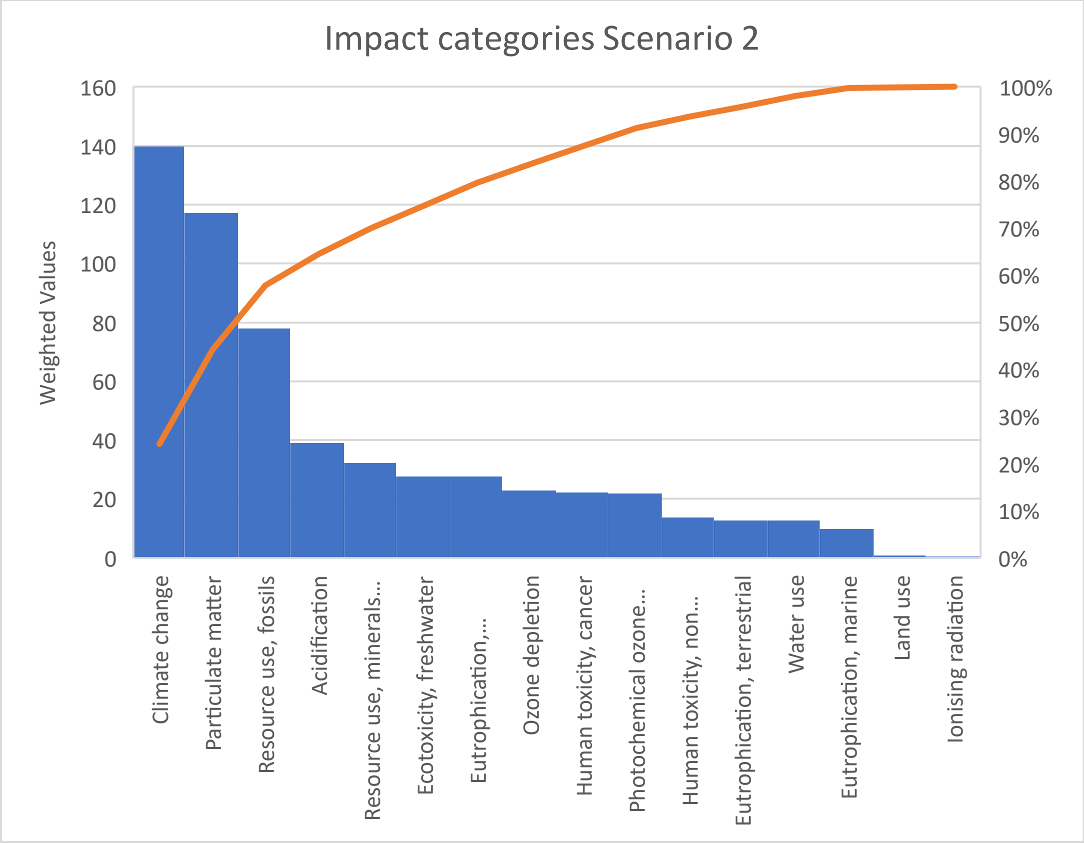

Figure 20*:* Pareto analysis of scenario 2 impact categories.

The pie chart represented in Figure 26 shows the different substances produced during the desalination process in scenario 2, with the highest emission being *Carbon dioxide, fossil*, making up 85% of the total. This underscores the high energy demand of reverse osmosis, mainly fueled by fossil fuels. Methane from fossils accounts for 11% of emissions, leading to global warming because of its high global warming potential. Moreover, *Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113*, a refrigerant linked to ozone depletion and climate change, accounts for 3% of emissions. *Dinitrogen monoxide* makes up 1% of the contributions, with other substances accounting for 0.4%.

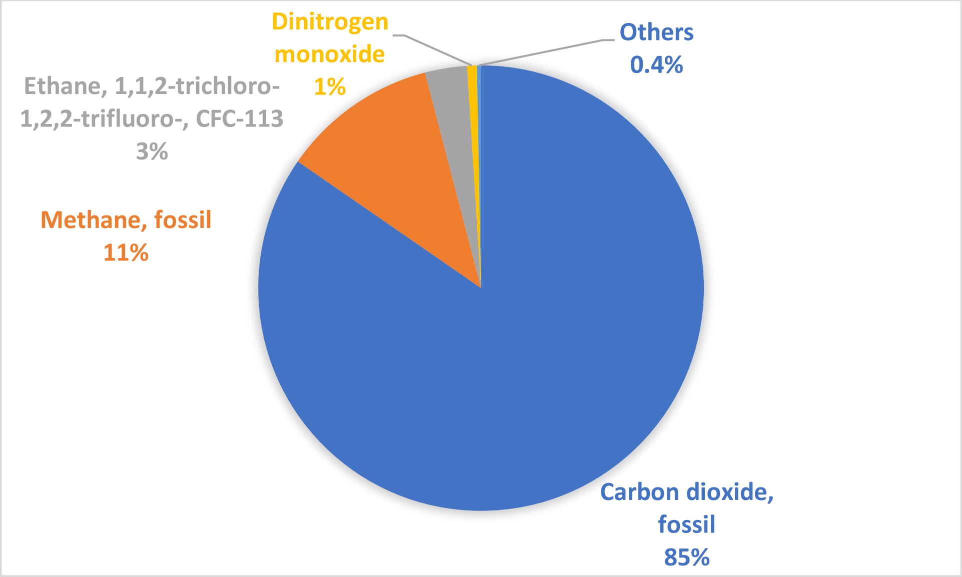

Figure 21: Piechart of the output substances of the desalination process in scenario 2.

Furthermore, the environmental implications of desalinated water extend beyond energy consumption. One key concern is brine production as a by-product of reverse osmosis. Brine, which contains high concentrations of salt, is discharged into marine environments, potentially disrupting ecosystems. Additionally, the presence of pyrite (FeS_2) in copper minerals within the tailings, typically ranging between 5% and 15%, increases the risk of developing acid mine drainage (AMD), especially when desalinated water is used (Abbadi & Mucsi, 2024). Unlike tailings generated with seawater, which generally do not produce AMD due to various mitigating factors, those associated with desalinated water may require additional neutralising agents or other preventive measures to control the formation of AMD. Moreover, the use of desalinated seawater can create operational challenges, leading to higher consumption of reagents. While many mining companies assert that AMD is not a concern, field observations suggest that this issue can still arise under certain conditions, particularly in northern Chile. Therefore, it is essential to carefully consider and discuss the potential for AMD and its environmental impact when using desalinated water in mining processes. The brine output is relevant to several impact categories, for eutrophication, the discharge of brine into marine environments can contribute to nutrient enrichment and subsequent eutrophication due to its high concentrations of salts and potential nutrients. Additionally, the risk of AMD from pyrite in tailings is associated with the *Acidification* impact category, as AMD can lead to the acidification of both soil and water.

In summary, the environmental effects of water management in copper concentration plants vary depending on the scenario. Scenario 1 focuses on the exhaustion of fossil fuels caused by energy-intensive water transportation methods. In contrast, scenario 2 stresses the higher levels of greenhouse gas emissions and potential environmental dangers linked to desalination and brine disposal. The results provide a more equitable perspective on the environmental obstacles presented by various water management techniques in copper mining.

5.5 Sensitivity analysis

A sensitivity analysis is a technique employed to evaluate the dependability and precision of input information. This study will assess how different chemicals and Te affect the environmental effects of the copper concentration process. Tellurium was chosen because of its major impact on the most influential category: *Resource use, minerals, and metals*. On the one hand, chemicals were selected for the sensitivity analysis because they differ between the water sources used in the copper concentration process, with distinct outputs required for seawater and desalinated water. The chemicals related to the desalinated plant were not under study for a sensitivity analysis. And the chemicals involved in the desalination plant are derived from a real-world case study in Chile, which provides a high level of accuracy.

The sensitivity analysis involves tracking the changes in the single score when adjusting a variable by 5% and 10%. After applying sensitivity tests on several chemicals of the copper concentration process, it was revealed no significant changes in the single score, indicating that the reagents under study have no significant impact by changing 5 or 10% and the results are stable across different scenarios, concluding that the chemicals are not generating any meaningful impact into the category Resource use, minerals and metals. Following a sensitivity analysis on the chemical inputs showing no notable changes in the single score among scenarios, a decision was made to conduct a sensitivity analysis specifically on Te. Tellurium is the main substance produced in the copper concentration process, making up 76% of the total output and being the primary factor in the impact category *Resource Use, Minerals, and Metals*.

SimaPro refers to the input of Te as the amount calculated through the mass balance of the copper production chain. The Te amount is based on the estimated amount of anode slime produced in the given region and the average Te content of the anode slime. The Te amount was then adjusted based on the assumption that the regions extract 70% of the global Te extracted in copper ores. Initial value of Te 6.56E-5 (Turner & Hischier, 2020). The sensitivity analysis carried out on Te, shows a direct correlation between its amount and the environmental consequences in scenario 1. Increasing the Te output by 5% and 10% resulted in a corresponding rise in the single score for this impact category. More precisely, an increase of 5% in Te led to a score increase of 0.16 from 4.63 to 4.79, while a 10% rise raised the score to 4.95. These findings indicate a direct correlation between Te production and its environmental impact. The steady increase in the score with the gradual increase in Te production shows that the element significantly influences the *Resource use, minerals, and metals* impact category. This stresses the significance of Te in impacting the environmental results of the copper beneficiation process in this situation.

In scenario 2, a similar investigation was carried out to assess the sensitivity of the Te output when desalinated water was used as the water source. Once again, it was proven that increasing Te production by 5% and 10% resulted in a rise in the score for the *Resource use, minerals, and metals* impact category and the single score. To be more specific, increasing the production of Te by 5% resulted in a rise of the single score from 5.21 to 5.37, with a further increase to 5.53 with a 10%

rise. Similar to scenario 1, there is a clear connection between Te production and its environmental effects. The increase in the single score shows that Te remains influential in the exhaustion of mineral and metal resources while using desalinated water in the copper beneficiation process.

The findings of the sensitivity analysis for scenario 1 (seawater) and scenario 2 (desalinated water) demonstrate a consistent pattern in how Te production influences environmental consequences, particularly in the *Resource Use, Minerals, and Metals* sector. In both cases, raising the Te output by 5% causes a 0.16 increase in the single score, while a 10% increase leads to a 0.32 rise in the single score. Nevertheless, the individual scores show differing absolute values in the two situations, indicating differences in overall effects when using seawater versus desalinated water despite a consistent pattern.

5.6 Recommendations

Several enhancements can be implemented to improve effectiveness and decrease the amount of Te extracted during copper mining and concentration processes (Table 6). A crucial aspect is the integration of automated ore sorting technologies, such as X-ray fluorescence or laser-based sorting, which can assist in pre-selecting high-quality copper ore before it undergoes the concentration process. This initial sorting process helps decrease the amount of Tellurium-rich material, enhancing overall effectiveness (Fogo et al., 2023).

Selective mining practices can help decrease the accidental removal of Te during mining processes. If possible, underground mining should be given preference over open-pit techniques. Subterranean mining usually causes minimal disruption to the surroundings, decreasing the processing of tellurium-bearing waste material. In addition, employing advanced drilling and blasting techniques like precision mining tools can help reduce the extraction of low-grade ores that may have higher amounts of Te. These techniques aim to decrease the extraction of Te at its origin by targeting the more concentrated copper ores (Bustamante & Gaustad, 2014).

Improving the focusing process itself is another crucial stage. Specifically, the flotation process can be improved to more effectively separate copper from other minerals such as Te. This might include adjusting the reagent schemes and flotation conditions to improve selectivity and guarantee Te separation from the copper concentrate (Vazifeh et al., 2010). Furthermore, other technologies like hydrothermal treatment or bioleaching can be used before the concentration step to decrease the strength of tellurium-containing minerals (Zhang et al., 2024). Using these methods, the efficiency of copper extraction and concentration processes can be improved, leading to a decrease in the extraction of Te and its related environmental effects. These advancements can help create a more environmentally friendly and economically sound method of copper mining by reducing the extraction of surplus byproducts such as Te. If the amount of Te cannot be minimised, utilising it in photovoltaic cells presents a viable solution to effectively harness this resource, thereby contributing to a circular economy (McNulty & Jowitt, 2022).

Although scenario 1 has a lower environmental impact across all categories, if desalinated water is the only available option, scenarios like Scenario 2 could be improved by investing in innovative desalination technologies. This is crucial for enhancing sustainability in water management within copper mining.

While Scenario 1 shows reduced environmental impacts in all categories, scenario 2, which uses desalinated water, can be improved by implementing new desalination technologies. In the copper mining industry in northern Chile, addressing water scarcity is crucial, and making improvements in desalination processes is necessary to enhance sustainable water management practices. By adopting advanced desalination technologies like solar desalination and hybrid systems combining reverse osmosis with other methods, we can notably decrease the environmental consequences of water procurement. These technologies are created to reduce energy consumption, decrease reliance on fossil fuels, and reduce brine production, addressing a major challenge of traditional desalination methods. In scenario 2, incorporating renewable energy like solar desalination could be advantageous in sunny regions like northern Chile (Isah et al., 2024).

Moreover, the hybrid desalination systems that integrate several methods have the potential to improve effectiveness by maximising water retrieval rates and minimising waste production. This is important in scenario 2, as the desalination plant increases the environmental impact, particularly in areas such as *Climate change* and *Resource use*. By implementing more effective systems, scenario 2 may see decreases in these areas, specifically in emissions related to energy. Furthermore, integrating these advancements into copper mining activities aligns with Chile's overall environmental goals, especially in lowering carbon emissions and enhancing resource efficiency. In addition, progress in desalination technology is needed since it is forbidden to use continental water in Chile for mining activities, as previously mentioned. In the end, advancements in desalination technology would not just improve the sustainability of scenario 2 but also boost Chile's prominence in the global copper industry by incorporating more sustainable methods in mineral processing (Farabi et al., 2024).

Table 6: Hotspots and recommendations for mitigating environmental impacts in copper mining processes, comparing seawater (scenario 1) and desalinated water (scenario 2).

Hotspot	***Scenario 1 or 2***	***Recommendations***
Ore selection	Both scenarios	Implement automated ore sorting to select high-quality copper ores early, reducing the amount of tellurium-rich material that enters the concentration process (Fogo et al., 2023).
Mining techniques	Both scenarios	Prioritize underground mining to minimize environmental disruption and reduce the extraction of tellurium-bearing waste. Use precision tools to target richer copper ores. (Bustamante & Gaustad, 2014).
Flotation process	Scenario 2	Adjust flotation reagents and conditions to improve the separation of copper from tellurium-containing minerals (Vazifeh et al., 2010). Consider techniques like hydrothermal treatment or bioleaching (Zhang et al., 2024).
Resource utilisation	Scenario 2	Explore the use of tellurium in photovoltaic cells to reduce wastage and support circular economy initiatives (McNulty & Jowitt, 2022).
Water management	Scenario 2	Invest in energy-efficient desalination technologies, such as solar or hybrid systems, to reduce environmental impacts and improve water management (Farabi et al., 2024).

6. Conclusions

This dissertation was mainly inspired by the energy transition, limited water resources, and the sustainability issues related to the copper concentration process during mining. Because Chile is the top copper producer globally and deals with severe water scarcity, it was selected as the primary focus for this examination. Chile is leading the way in various initiatives that utilise seawater and desalinated water for copper processing due to the country's limited reserves of continental water. As a result, two situations were evaluated: one utilising seawater and the other using desalinated water.

The primary goal of this study was to assess the environmental effects linked to varying levels of copper concentration in each situation and to thoroughly compare them. Both situations were thoroughly examined using various methods and analytical tools to detect the most significant impact areas and offer recommendations. After conducting a thorough review of various texts, it was determined that LCA is essential for evaluating the environmental impact of mining activities. Noting that chemical amounts used in copper processing can greatly differ each day, depending on the mineral type and company methods, presents challenges in evaluation. Nevertheless, mean values were used to ensure consistency in the investigation.

The EF 3.1 framework was utilised, as suggested by the European Union and commonly used in current research since it is the most up-to-date method. The primary finding indicates that scenario 2 exhibits a greater environmental impact than scenario 1, a conclusion supported by the deviation results obtained during the analysis. The main impact category highlighted in both scenarios was *Resource use, mineral and metal*, with Te recognised as an output material. The results show different environmental effects in the two situations if the process of copper concentration is excluded. In the first scenario, the main issue is the depletion of fossil fuels due to the energy-intensive transportation of seawater, emphasising the use of resources and fossils as the most important impact category. On the other hand, scenario 2 highlights higher greenhouse gas emissions and environmental dangers associated with using desalinated water, with the desalination plant being a major contributor to higher resource usage and environmental impacts, leading Climate Change to be the primary focus. These results give a deeper understanding into the environmental challenges presented by varying water management approaches in copper mining, specifically regarding the balancing act between fossil fuel usage and emissions from desalination methods.

Additionally, while chemicals used in the copper beneficiation process did not affect the impact category of *Resource use, minerals, and metals*, findings from the sensitivity analysis related to Te output demonstrated that even slight increases in Te can significantly influence the overall environmental consequences, particularly regarding the depletion of mineral and metal resources. Both scenarios could benefit from the integration of renewable energy sources to reduce the energy intensity of operations, such as those involved in desalination. This study was limited to a North Chilean context, utilising average values pertinent to the region.

Future studies could focus on comparing copper concentration methods in regions with varying water scarcity issues, such as Australia or Peru, to develop location-specific sustainability tactics based on the insights from this thesis and anticipate future water scarcity problems. Furthermore, investigating how to incorporate new technologies like live monitoring and adaptive management methods might improve water usage efficiency and try to reduce in a way the environmental effects of copper processing. Furthermore, the exploration of circular economy strategies to manage the outputs generated, such as reusing process water or by-products, could be a solution for reducing the depletion of resources. Additionally, consider and assess the possibility and influence of new renewable energy technologies, like solar and wind power, on different stages of the desalination or the copper concentration process could lead to reducing the environmental impacts related to water management in mining operations. These studies would not just boost academic knowledge but also help the industry in moving towards sustainable practices to address worldwide environmental issues.

7. References

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Appendix A – Model developed for Scenario 1: Seawater

Table 7: Modelling of scenario 1, Copper concentration process with seawater as water source (Copper concentration stage).

Inputs & Outputs	***Quantity***	***Unit***
SimaPro Input References		
Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore		
Copper	0,27279637	kg
Gangue	96,4279354	kg
Gold	2,5892E-06	kg
Molybdenum	0,00423594	kg
Rhenium	2,0946E-06	kg
Selenium	0,0007621	kg
Silver	9,2177E-05	kg
Tellurium	6,5652E-05	kg
Occupation, mineral extraction site	0,00266241	m2a
Transformation, from unspecified	8,8518E-05	m2
Transformation, to mineral extraction site	8,8518E-05	m2
Water, salt, ocean	2,5	m3
Aluminium hydroxide factory {GLO}| market for aluminium hydroxide factory | Cut-off, U	4,2807E-10	p
Aluminium sulfate, powder {RoW}| market for aluminium sulfate, powder | Cut-off, U	1,1562E-07	kg
Blasting {GLO}| market for blasting | Cut-off, U	0,04278309	kg
Carbon disulfide {GLO}| market for carbon disulfide | Cut-off, U	8,8981E-08	kg
Chemical, inorganic {GLO}| market for chemical, inorganic | Cut-off, U	0,03290493	kg
Chemical, organic {GLO}| market for chemical, organic | Cut-off, U	0,0115105	kg
Conveyor belt {GLO}| market for conveyor belt | Cut-off, U	3,8551E-06	m
Copper sulfate {GLO}| market for copper sulfate | Cut-off, U	3,956E-07	kg
Diesel {RoW}| market for diesel | Cut-off, U	1,9657E-07	kg
Dithiocarbamate-compound {GLO}| market for dithiocarbamate-compound | Cut-off, U	1,9262E-07	kg
Iron pellet {GLO}| market for iron pellet | Cut-off, U	1,6258E-06	kg
Mine infrastructure, open cast, non-ferrous metal {GLO}| market for mine infrastructure, open cast, non-ferrous metal | Cut-off, U	4,8076E-10	p
Mine infrastructure, underground, non-ferrous metal {GLO}| market for mine infrastructure, underground, non-ferrous metal | Cut-off, U	2,0974E-10	p
Potassium carbonate {GLO}| market for potassium carbonate | Cut-off, U	1,8848E-09	kg
Steel, chromium steel 18/8, hot rolled {GLO}| market for steel, chromium steel 18/8, hot rolled | Cut-off, U	0,03685798	kg
Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U	2,8735E-07	kg
Sodium ethyl xanthate {RoW}| sodium ethyl xanthate production | Cut-off, S	1156,95	mg
Disodium disulphite {GLO}| disodium disulphite production | Cut-off, S	8330,04	mg
4-methyl-2-pentanone {RoW}| 4-methyl-2-pentanone production | Cut-off, S	257,1	mg
Polyacrylamide {GLO}| polyacrylamide production | Cut-off, S	756,3	mg
1-methoxy-2-propanol {GLO}| 1-methoxy-2-propanol production | Cut-off, S	0	mg

Inputs & Outputs	***Quantity***	***Unit***
SimaPro Input References		
Diesel, burned in building machine {GLO}| market for diesel, burned in building machine | Cut-off, U	0,0027976	MJ
Electricity, high voltage {CL}| market for electricity, high voltage | Cut-off, U	0,66051889	kWh
Electricity, medium voltage {CL}| market for electricity, medium voltage | Cut-off, U	0,36986925	kWh
SimaPro Outputs references		
Emissions to air		
Antimony, ion	4,6535E-09	kg
Arsenic, ion	3,4901E-08	kg
Barium (II)	9,6484E-12	kg
Beryllium (II)	6,053E-08	kg
Boron	2,3267E-07	kg
Cadmium (II)	2,5594E-09	kg
Carbon dioxide, fossil	0,02887363	kg
Carbon disulfide	0,00505815	kg
Chromium (III)	2,3267E-06	kg
Cobalt (II)	4,6535E-07	kg
Copper, ion	1,1634E-06	kg
Cyanide	2,9289E-16	kg
Fluorine	2,2104E-05	kg
Lead (II)	3,2574E-07	kg
Manganese (II)	2,2104E-05	kg
Mercury (II)	1,1634E-09	kg
Molybdenum (VI)	7,414E-15	kg
Nickel (II)	1,8614E-06	kg
Nitrogen oxides	2,7746E-08	kg
Particulates, < 2.5 um	0,0011437	kg
Particulates, > 10 um	0,01183132	kg
Particulates, > 2.5 um, and < 10um	0,01029246	kg
Selenium (IV)	1,1634E-09	kg
Water/m3	0,00452897	m3
Zinc (II)	4,4208E-06	kg
Emissions to water		
Aluminium (III)	7,8216E-07	kg
Arsenic, ion	2,6717E-08	kg
BOD5 (Biological Oxygen Demand)	9,4345E-05	kg
Cadmium (II)	2,8591E-09	kg
Calcium	0,0062113	kg
Chromium (III)	4,9497E-09	kg
Cobalt (II)	7,0723E-09	kg
COD (Chemical Oxygen Demand)	9,4344E-05	kg
Copper, ion	7,1679E-08	kg
Cyanide	3,0927E-05	kg
DOC, Dissolved Organic Carbon	3,6908E-05	kg
Iron, ion	2,6314E-06	kg

Inputs & Outputs	***Quantity***	***Unit***
SimaPro Outputs references		
Lead (II)	2,5335E-08	kg
Manganese (II)	2,2329E-07	kg
Mercury (II)	3,4082E-10	kg
Nickel (II)	2,2023E-07	kg
Nitrogen, organic bound	0,00020591	kg
Sulfate	0,02133884	kg
Suspended solids, unspecified	4,6788E-05	kg
TOC, Total Organic Carbon	3,6907E-05	kg
Water, CL	0,00452892	m3
Water, CL	2,8628E-07	m3
Zinc (II)	6,8683E-07	kg
Emissions to soil	87,4961165	kg
Final waste flows	49,5593453	kg
Waste		
Non-sulfidic tailing, off-site {GLO}| market for non-sulfidic tailing, off-site | Cut-off, U		
Sulfidic tailings, from copper mine operation {CL}| market for sulfidic tailings, from copper mine operation | Cut-off, U		

Table 8: Modelling of scenario 1, Copper concentration process with seawater as water source (Pipe stage)

Inputs & Outputs	***Quantity***	***Unit***
SimaPro Input References		
HDPE pipe, DN 900, (SCALED PIPE)| polyethylene pipe production, DN 200, SDR 41 | Cut-off, U	1	m
Inputs		
Extrusion, plastic pipes {GLO}| market for extrusion, plastic pipes | Cut-off, U	147,676785	kg
Plastic processing factory {GLO}| market for plastic processing factory | Cut-off, U	1,0408E-07	p
Polyethylene, high density, granulate {GLO}| market for polyethylene, high density, granulate | Cut-off, U	147,676785	kg
Electricity, medium voltage {AU}| market for electricity, medium voltage | Cut-off, U	0,00356551	kWh
Electricity, medium voltage {NZ}| market for electricity, medium voltage | Cut-off, U	0,00069879	kWh
Electricity, medium voltage {RAF}| market group for electricity, medium voltage | Cut-off, U	0,01177626	kWh
Electricity, medium voltage {RAS}| market group for electricity, medium voltage | Cut-off, U	0,21529369	kWh
Electricity, medium voltage {RLA}| market group for electricity, medium voltage | Cut-off, U	0,02346504	kWh
Electricity, medium voltage {RNA}| market group for electricity, medium voltage | Cut-off, U	0,07520071	kWh
Heat, district or industrial, natural gas {CA-QC}| market for heat, district or industrial, natural gas | Cut-off, U	0,06680973	MJ
Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	4,06569027	MJ
Heat, district or industrial, other than natural gas {CA-QC}| market for heat, district or industrial, other than natural gas | Cut-off, U	0,00191362	MJ
Heat, district or industrial, other than natural gas {RoW}| market for heat, district or industrial, other than natural gas | Cut-off, U	4,13058638	MJ
SimaPro Output References		
Waste to treatment		
Waste polyethylene {BR}| market for waste polyethylene | Cut-off, U	0,8641887	kg
Waste polyethylene {CO}| market for waste polyethylene | Cut-off, U	0,05774176	kg
Waste polyethylene {CY}| market for waste polyethylene | Cut-off, U	0,00436692	kg
Waste polyethylene {IN}| market for waste polyethylene | Cut-off, U	0,02384941	kg
Waste polyethylene {PE}| market for waste polyethylene | Cut-off, U	0,00963489	kg
Waste polyethylene {RoW}| market for waste polyethylene | Cut-off, U	6,04979893	kg
Waste polyethylene {ZA}| market for waste polyethylene | Cut-off, U	0,02264725	kg

Table 9: Modelling of scenario 1, Copper concentration process with seawater as water source (Pumping station stage).

Inputs & Outputs	***Quantity***	***Unit***
SimaPro Input References		
Seawater pump, for industrial applications (Scaled) {GLO}| water pump production, 22kW | Cut-off, U	1	p
Inputs		
Aluminium scrap, post-consumer {GLO}| aluminium scrap, post-consumer, Recycled Content cut-off | Cut-off, U	-34,09	kg
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	34,09	kg
Bronze {GLO}| market for bronze | Cut-off, U	2046	kg
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	426	kg
Bronze scrap, post-consumer {GLO}| market for bronze scrap, post-consumer | Cut-off, U	-2046	kg
Polyvinylchloride, emulsion polymerised {GLO}| market for polyvinylchloride, emulsion polymerised | Cut-off, U	6,54	kg
Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	44,6	kg
Steel, stainless 304, quarto plate/kg/RNA	1565,7	kg
Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U	11,96	kg
Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U	140	kWh
Heat, district or industrial, natural gas {GLO}| market group for heat, district or industrial, natural gas | Cut-off, U	1330	MJ
Hot water tank factory {GLO}| market for hot water tank factory | Cut-off, U	0,0000002	p
SimaPro Output References		
Waste to treatment		
Scrap copper {CH}| market for scrap copper | Cut-off, U	6,34	kg
Scrap copper {Europe without Switzerland}| market for scrap copper | Cut-off, U	135,2	kg
Scrap copper {RoW}| market for scrap copper | Cut-off, U	278,6	kg
Scrap steel {CH}| market for scrap steel | Cut-off, U	0,47	kg
Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	374	kg
Scrap steel {RoW}| market for scrap steel | Cut-off, U	1161	kg
Waste polyvinylchloride product {CH}| market for waste polyvinylchloride product | Cut-off, U	0,46	kg
Waste polyvinylchloride product {Europe without Switzerland}| market for waste polyvinylchloride product | Cut-off, U	13,6	kg
Waste polyvinylchloride product {RoW}| market for waste polyvinylchloride product | Cut-off, U	35,6	kg
Waste rubber, unspecified {CH}| market for waste rubber, unspecified | Cut-off, U	0,243	kg
Waste rubber, unspecified {Europe without Switzerland}| market for waste rubber, unspecified | Cut-off, U	5,71	kg
Waste rubber, unspecified {RoW}| market for waste rubber, unspecified | Cut-off, U	5,71	kg

Appendix B – Model developed for Scenario 2: Desalinated water

Table 10: Modelling of scenario 2, Copper concentration process with desalinated as water source (Desalination plant stage).

Inputs & Outputs	***Quantity***	***unit***
Simapro Input References		
Water treatement {GLO}| tap water production, seawater reverse osmosis, conventional pretreatment, enhance module, two stages | Cut-off, U	1	kg
inputs		
Water, salt, ocean	0,0025	m3
Carbon dioxide, liquid {RER}| market for carbon dioxide, liquid | Cut-off, U	5,82555E-06	kg
Carbon dioxide, liquid {RoW}| market for carbon dioxide, liquid | Cut-off, U	2,76744E-05	kg
Chlorine, liquid {RER}| market for chlorine, liquid | Cut-off, U	1,66693E-08	kg
Chlorine, liquid {RoW}| market for chlorine, liquid | Cut-off, U	8,33307E-08	kg
Epoxy resin, liquid {RER}| market for epoxy resin, liquid | Cut-off, U	5,01353E-09	kg
Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | Cut-off, U	2,37999E-08	kg
Glass fibre {GLO}| market for glass fibre | Cut-off, U	3,69112E-07	kg
Iron(III) chloride, without water, in a 12% iron solution state {GLO}| market for iron(III) chloride, without water, in a 12% iron solution state | Cut-off, U	2,06296E-05	kg
Lime, hydrated, packed {RER}| market for lime, hydrated, packed | Cut-off, U	3,66135E-07	kg
Lime, hydrated, packed {RoW}| market for lime, hydrated, packed | Cut-off, U	4,31339E-05	kg
Polyacrylamide {GLO}| market for polyacrylamide | Cut-off, U	0,00000105	kg
Polycarboxylates, 40% active substance {RER}| market for polycarboxylates, 40% active substance | Cut-off, U	1,48436E-06	kg
Polycarboxylates, 40% active substance {RoW}| market for polycarboxylates, 40% active substance | Cut-off, U	3,00564E-06	kg
Polyvinylidenchloride, granulate {RER}| market for polyvinylidenchloride, granulate | Cut-off, U	0,000155378	kg
Polyvinylidenchloride, granulate {RoW}| market for polyvinylidenchloride, granulate | Cut-off, U	0,000314622	kg
Seawater reverse osmosis module {GLO}| seawater reverse osmosis module production, 8-inch spiral wound, enhanced | Cut-off, U	1,69119E-06	m2
Sodium hydrogen sulfite {GLO}| market for sodium hydrogen sulfite | Cut-off, U	0,0000237	kg
Sodium hypochlorite, without water, in 15% solution state {RER}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, U	2,40503E-06	kg
Sodium hypochlorite, without water, in 15% solution state {RoW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, U	1,1417E-05	kg
Sulfuric acid {RER}| market for sulfuric acid | Cut-off, U	1,10307E-05	kg
Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	8,43193E-05	kg
Tap water {GLO}| market group for tap water | Cut-off, U	0,000130549	kg
Water works, capacity 6.23E10l/year {GLO}| water works construction, capacity 6.23E10l/year, seawater reverse osmosis, conventional pretreatment | Cut-off, U	5,3526E-13	p
Disodium disulphite {GLO}| disodium disulphite production | Cut-off, U	0,00001125	kg
Citric acid {GLO}| market for citric acid | Cut-off, S	0,000051	kg
Neutralising agent, sodium hydroxide-equivalent {GLO}| sodium hydroxide to generic market for neutralising agent | Cut-off, S	2,5025E-06	kg
Sodium phosphate {RER}| market for sodium phosphate | Cut-off, S	0,0000025	kg
Electricity, low voltage {CL}| market for electricity, low voltage | Cut-off, U	0,003052	kwh
Simapro Output References		

Inputs & Outputs	***Quantity***	***Unit***
Emissions to air		
Carbon dioxide, biogenic	0,0000184	kg
Emissions to water		
Bicarbonate, ion	0,0003254	kg
Boron	0,00001027	kg
Calcium	0,00101434	kg
Carbonate	0,0000027	kg
Chloride	0,0480582	kg
Fluoride	0,00000249	kg
Magnesium	0,00322539	kg
Potassium (I)	0,00096182	kg
Sodium	0,02671069	kg
Strontium (II)	0,00003248	kg
Sulfate	0,00672072	kg
Water, GLO	0,000818182	m3
Waste to treatment		
Waste glass pane in burnable frame {CH}| market for waste glass pane in burnable frame | Cut-off, U	3,34929E-09	kg
Waste glass pane in burnable frame {RoW}| market for waste glass pane in burnable frame | Cut-off, U	3,94576E-07	kg
Waste plastic, mixture {BR}| market for waste plastic, mixture | Cut-off, U	5,21987E-05	kg
Waste plastic, mixture {CO}| market for waste plastic, mixture | Cut-off, U	3,48771E-06	kg
Waste plastic, mixture {CY}| market for waste plastic, mixture | Cut-off, U	2,6377E-07	kg
Waste plastic, mixture {IN}| market for waste plastic, mixture | Cut-off, U	1,44055E-06	kg
Waste plastic, mixture {PE}| market for waste plastic, mixture | Cut-off, U	5,81966E-07	kg
Waste plastic, mixture {RER}| market group for waste plastic, mixture | Cut-off, U	4,52397E-05	kg
Waste plastic, mixture {RoW}| market for waste plastic, mixture | Cut-off, U	0,00036542	kg
Waste plastic, mixture {ZA}| market for waste plastic, mixture | Cut-off, U	1,36794E-06	kg

Table 11: Modelling of scenario 2, Copper concentration process with desalinated as water source (Copper concentration stage).

Inputs & Outputs	***Quantity***	***Unit***
Copper concentrate, sulfide ore (CL) copper mine operation and beneficiation, sulfide ore		
SimaPro Input References		
Copper	0,272796368	kg
Gangue	96,42793536	kg
Gold	2,58923E-06	kg
Molybdenum	0,004235938	kg
Rhenium	2,09465E-06	kg
Selenium	0,000762104	kg
Silver	9,21766E-05	kg
Tellurium	6,56524E-05	kg
Occupation, mineral extraction site	0,002662407	m2a
Transformation, from unspecified	8,85176E-05	m2
Transformation, to mineral extraction site	8,85176E-05	m2
Aluminium hydroxide factory {GLO}| market for aluminium hydroxide factory | Cut-off, U	4,28068E-10	p
Aluminium sulfate, powder {RoW}| market for aluminium sulfate, powder | Cut-off, U	1,15619E-07	kg
Blasting {GLO}| market for blasting | Cut-off, U	0,042783092	kg
Carbon disulfide {GLO}| market for carbon disulfide | Cut-off, U	8,89806E-08	kg
Chemical, inorganic {GLO}| market for chemical, inorganic | Cut-off, U	0,032904933	kg
Chemical, organic {GLO}| market for chemical, organic | Cut-off, U	0,011510505	kg
Conveyor belt {GLO}| market for conveyor belt | Cut-off, U	3,85508E-06	m
Copper sulfate {GLO}| market for copper sulfate | Cut-off, U	3,95596E-07	kg
Diesel {RoW}| market for diesel | Cut-off, U	1,96566E-07	kg
Dithiocarbamate-compound {GLO}| market for dithiocarbamate-compound | Cut-off, U	1,92617E-07	kg
Iron pellet {GLO}| market for iron pellet | Cut-off, U	1,62579E-06	kg
Lime, packed {RoW}| market for lime, packed | Cut-off, U	205680	mg
Mine infrastructure, open cast, non-ferrous metal {GLO}| market for mine infrastructure, open cast, non-ferrous metal | Cut-off, U	4,80765E-10	p
Mine infrastructure, underground, non-ferrous metal {GLO}| market for mine infrastructure, underground, non-ferrous metal | Cut-off, U	2,09743E-10	p
Potassium carbonate {GLO}| market for potassium carbonate | Cut-off, U	1,88477E-09	kg
Steel, chromium steel 18/8, hot rolled {GLO}| market for steel, chromium steel 18/8, hot rolled | Cut-off, U	0,036857982	kg
Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U	2,87348E-07	kg
Sodium ethyl xanthate {RoW}| sodium ethyl xanthate production | Cut-off, S	1156,95	mg
Disodium disulphite {GLO}| disodium disulphite production | Cut-off, S	8330,04	mg
Polyacrylamide {GLO}| polyacrylamide production | Cut-off, S	630,25	mg
1-methoxy-2-propanol {GLO}| 1-methoxy-2-propanol production | Cut-off, S	128,55	mg
C16-18 fatty alcohol from palm oil (No. 13a - Matrix), at plant, 100% active substance/EU-27	822,7	mg
Diesel, burned in building machine {GLO}| market for diesel, burned in building machine | Cut-off, U	0,002797603	MJ
Electricity, high voltage {CL}| market for electricity, high voltage | Cut-off, U	0,660518887	kWh
Electricity, medium voltage {CL}| market for electricity, medium voltage | Cut-off, U	0,369869247	kWh

Inputs & Outputs	***Quantity***	***Unit***
SimaPro Output references		
Emissions to Air		
Antimony, ion	4,6535E-09	kg
Arsenic, ion	3,49012E-08	kg
Barium (II)	9,64843E-12	kg
Beryllium (II)	6,05297E-08	kg
Boron	2,33E-07	kg
Cadmium (II)	2,55942E-09	kg
Carbon dioxide, fossil	0,028873634	kg
Carbon disulfide	0,005058149	kg
Chromium (III)	2,32675E-06	kg
Cobalt (II)	4,6535E-07	kg
Copper, ion	1,16337E-06	kg
Cyanide	2,92886E-16	kg
Fluorine	2,21041E-05	kg
Lead (II)	3,25745E-07	kg
Manganese (II)	2,21041E-05	kg
Mercury (II)	1,16337E-09	kg
Molybdenum (VI)	7,41398E-15	kg
Nickel (II)	1,8614E-06	kg
Nitrogen oxides	2,77461E-08	kg
Particulates, < 2.5 um	0,001143703	kg
Particulates, > 10 um	0,011831321	kg
Particulates, > 2.5 um, and < 10um	0,010292463	kg
Selenium (IV)	1,16337E-09	kg
Water/m3	0,004528972	m3
Zinc (II)	4,42082E-06	kg
Emissions to Water		
Aluminium (III)	7,82157E-07	kg
Arsenic, ion	2,67172E-08	kg
BOD5 (Biological Oxygen Demand)	9,43454E-05	kg
Cadmium (II)	2,85915E-09	kg
Calcium	0,006211301	kg
Chromium (III)	4,9497E-09	kg
Cobalt (II)	7,07229E-09	kg
COD (Chemical Oxygen Demand)	9,43443E-05	kg
Copper, ion	7,16787E-08	kg
Cyanide	3,0927E-05	kg
DOC, Dissolved Organic Carbon	3,69083E-05	kg
Iron, ion	2,63139E-06	kg
Lead (II)	2,53352E-08	kg
Manganese (II)	2,23289E-07	kg
Mercury (II)	3,40816E-10	kg
Nickel (II)	2,20227E-07	kg
Nitrogen, organic bound	0,000205914	kg

Inputs & Outputs	***Quantity***	***Unit***
Sulfate	0,021338845	kg
Suspended solids, unspecified	4,67878E-05	kg
TOC, Total Organic Carbon	3,69071E-05	kg
Water, CL	0	m3
Water, CL	0	m3
Zinc (II)	6,86833E-07	kg
Waste		
Non-sulfidic tailing, off-site {GLO}| market for non-sulfidic tailing, off-site | Cut-off, U	87,49611653	kg
Sulfidic tailings, from copper mine operation {CL}| market for sulfidic tailings, from copper mine operation | Cut-off, U	49,55934533	kg

Table 12: Modelling of scenario 2, Copper concentration process with desalinated as water source (Pipe stage).

Inputs & Outputs	Quantity	unit
SimaPro Input References		
HDPE pipe, DN 900, (SCALED PIPE)| polyethylene pipe production, DN 200, SDR 41 | Cut-off, U	1	m
Inputs		
Extrusion, plastic pipes {GLO}| market for extrusion, plastic pipes | Cut-off, U	147,676785	kg
Plastic processing factory {GLO}| market for plastic processing factory | Cut-off, U	1,0408E-07	p
Polyethylene, high density, granulate {GLO}| market for polyethylene, high density, granulate | Cut-off, U	147,676785	kg
Electricity, medium voltage {AU}| market for electricity, medium voltage | Cut-off, U	0,00356551	kwh
Electricity, medium voltage {NZ}| market for electricity, medium voltage | Cut-off, U	0,00069879	kwh
Electricity, medium voltage {RAF}| market group for electricity, medium voltage | Cut-off, U	0,01177626	kwh
Electricity, medium voltage {RAS}| market group for electricity, medium voltage | Cut-off, U	0,21529369	kwh
Electricity, medium voltage {RLA}| market group for electricity, medium voltage | Cut-off, U	0,02346504	kwh
Electricity, medium voltage {RNA}| market group for electricity, medium voltage | Cut-off, U	0,07520071	kwh
Heat, district or industrial, natural gas {CA-QC}| market for heat, district or industrial, natural gas | Cut-off, U	0,06680973	mj
Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	4,06569027	mj
Heat, district or industrial, other than natural gas {CA-QC}| market for heat, district or industrial, other than natural gas | Cut-off, U	0,00191362	mj
Heat, district or industrial, other than natural gas {RoW}| market for heat, district or industrial, other than natural gas | Cut-off, U	4,13058638	mj
simapro output references		
Waste to treatment		
Waste polyethylene {BR}| market for waste polyethylene | Cut-off, U	0,8641887	kg
Waste polyethylene {CO}| market for waste polyethylene | Cut-off, U	0,05774176	kg
Waste polyethylene {CY}| market for waste polyethylene | Cut-off, U	0,00436692	kg
Waste polyethylene {IN}| market for waste polyethylene | Cut-off, U	0,02384941	kg
Waste polyethylene {PE}| market for waste polyethylene | Cut-off, U	0,00963489	kg
Waste polyethylene {RoW}| market for waste polyethylene | Cut-off, U	6,04979893	kg
Waste polyethylene {ZA}| market for waste polyethylene | Cut-off, U	0,02264725	kg

Table 13: Modelling of scenario 2, Copper concentration process with desalinated as water source (Pump station stage).

Inputs & Outputs	**Quantity**	**unit**
Simapro input references		
Freshwater pump, for industrial applications (Scaled) {GLO}| water pump production, 22kW | Cut-off, U	1	p
Inputs		
Aluminium scrap, post-consumer {GLO}| aluminium scrap, post-consumer, Recycled Content cut-off | Cut-off, U	-33,35	kg
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	33,35	kg
Cast iron {GLO}| market for cast iron | Cut-off, U	2002	kg
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	417	kg
Iron scrap, unsorted {GLO}| iron scrap, unsorted, Recycled Content cut-off | Cut-off, U	-2002	kg
Polyvinylchloride, emulsion polymerised {GLO}| market for polyvinylchloride, emulsion polymerised | Cut-off, U	6,4	kg
Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	43,6	kg
Steel, chromium steel 18/8, hot rolled {GLO}| market for steel, chromium steel 18/8, hot rolled | Cut-off, U	1532	kg
Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U	11,68	kg
Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U	140	kwh
Heat, district or industrial, natural gas {GLO}| market group for heat, district or industrial, natural gas | Cut-off, U	1330	mj
Hot water tank factory {GLO}| market for hot water tank factory | Cut-off, U	0,0000002	p
simapro output references		
Waste to treatment		
Scrap copper {CH}| market for scrap copper | Cut-off, U	6,21	kg
Scrap copper {Europe without Switzerland}| market for scrap copper | Cut-off, U	132,3	kg
Scrap copper {RoW}| market for scrap copper | Cut-off, U	278,6	kg
Scrap steel {CH}| market for scrap steel | Cut-off, U	0,47	kg
Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	374	kg
Scrap steel {RoW}| market for scrap steel | Cut-off, U	1161	kg
Waste polyvinylchloride product {CH}| market for waste polyvinylchloride product | Cut-off, U	0,46	kg
Waste polyvinylchloride product {Europe without Switzerland}| market for waste polyvinylchloride product | Cut-off, U	13,6	kg
Waste polyvinylchloride product {RoW}| market for waste polyvinylchloride product | Cut-off, U	35,6	kg
Waste rubber, unspecified {CH}| market for waste rubber, unspecified | Cut-off, U	0,243	kg
Waste rubber, unspecified {Europe without Switzerland}| market for waste rubber, unspecified | Cut-off, U	5,71	kg
Waste rubber, unspecified {RoW}| market for waste rubber, unspecified | Cut-off, U	5,71	kg