


Review

Environmental Management Strategies in the Copper Mining Industry in Chile to Address Water and Energy Challenges—Review

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Abstract: The mining industry faces diverse challenges to maintain sustainable production, particularly regarding critical water and energy supplies. As a significant player in the copper mining industry, Chile has become a global reference. Therefore, this research analyses the distinct challenges of the Chilean copper mining industry in terms of water and energy. We also identified ten key challenges that the Chilean copper mining industry must address to remain competitive and relevant. Several mining companies were examined to review and understand the different types of Environmental Management Initiatives (EMIs) adopted. The most prevailing strategies involved implementing Environmental Management Systems, which allow organisations to define, implement, and track their specific goals and standards. This review acknowledged four relevant water-related initiatives, including seawater use, community strategic plans, general environmental monitoring programs, and water recycling and recirculation systems. In terms of energy, the key initiatives included energy efficiency projects, the use of Non-Conventional Renewable Energy (NCRE), and mine process optimisation. The benefits of implementing EMIs are multiple, with the most relevant being ensuring continuous operation, cost reduction, and improved Social License to Operate (SLO) outcomes.

Keywords: mining industry; mining challenges; social license to operate; environmental strategies; sustainable mining; environmental management; copper mining; sustainable development goals



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1. Introduction

Sustainable development in the mining industry is a critical concern for companies because it covers multiple environmental, social, and economic approaches. The principal aim of sustainable development is to find the equilibrium between environmental, social, and economic aspects to maintain the system's stability [1]. In this sense, defining mining sustainability is a complex task because of the multidimensional definition of sustainability. However, the primary concern of the environmental sustainability of the mining industry is to avoid and reduce environmental impact at different stages of the mining life cycle, where the mining industry needs to anticipate possible negative effects that its operations may generate [2].

Mining companies need a robust structure and adequate leadership to implement diverse, sustainable strategies to reduce environmental impacts and an environmentally friendly operation. Hence, they should implement an action plan for environmental improvement as part of the companies' strategic plan [3]. In the socioeconomic aspect, there are various interest groups which mining processes can affect in a negative or positive manner. For this reason, the mining industry has an important responsibility to cover the various requirements of these groups. Evidence shows the consequences of a mining operation closing prematurely, such as a direct or indirect reduction in employment in the

region, investment, town and community loss, among others [1,2]. The main characteristic of mining companies is their ability to provide direct employment and local business on a local and regional scale. In this context, the creation of new jobs, programs to improve local communities' skills, and investment opportunities to improve the regional infrastructure are parts of the activities carried out by the mining industry to ensure adequate socio-sustainability growth [2,3].

However, as a mining operation stakeholder, it is vital for an investor that the process is profitable while also maintaining the balance between social and environmental aspects, which is why it is essential to maximise the efficiency of the processes with adequate resource management. Therefore, mining industry sustainability studies have always focused on clean environmental aspects such as waste management. According to Aznar-Sánchez et al. (2018), waste management research has increased from 1988 to 2017 and now accounts for the majority of 40% of total mining sustainability research. Nonetheless, there is a scarcity of studies on the sustainability challenges related to water and energy management [4].

Sustainable water and energy management practices in mining are not a new concern. In fact, there is some research on sustainable practices in mining which will be discussed in the following sections. However, there is still a lack of research which evaluates environmental management strategies in the mining industry to face the water and energy challenges of the sector. Some strategies have been studied, and one of them is community strategic plans. Companies have developed different activities such as educational programs, training programs, or improvement in infrastructure programs [5]. Among these cases, communities and companies developed an alliance to improve water source access and reduce stakeholder conflicts. Other sustainable strategies focused on improving energy-infrastructure-assisted communities in enhancing their energy efficiency [5].

Aside from a lack of research, the issue of water demand in times of water shortage has always been overlooked due to high mining profits, excessive funding, and operational fares [6]. However, some countries have applied diverse strategies to optimise water and energy consumption. Some examples are in the literature, such as the systematic water measurement system, which can reduce water consumption and improve response time with any issue [7]. Another example is seawater use, which has been a natural alternative for companies to ensure continuous operations, and some authors argue that its use will increase over time and can help to address the hydro shortage problem [8–10]. An example from China also stated that recycling water is an effective strategy to maintain water balance [11].

In terms of energy, studies have shown many benefits that can be provided by renewable technologies, with solar power being one of the most used renewable energy sources for mining companies in Chile [12–15]. Solar energy has become an alternative for companies because of the high electricity demand and cost. Solar technology has also provided environmental and social benefits. It reduces greenhouse gaseous (GHG) emissions and fossil fuel dependency in the electrical system, especially in Chile [13]. However, most countries continue to face technological barriers and a lack of literature to be used as a guideline, limiting the effective implementation of sustainability-oriented strategies [16].

There are numerous challenges that companies must face to achieve successful sustainable development. Hence, taking Chile as the primary subject of this research, the article analyses the distinct challenges of the Chilean copper mining industry related to water and energy. In addition, we also described and analysed several mining companies operating in the country. This study focussed on how the copper mining industry develops sustainable practices to address water and energy issues. This research is vital in highlighting the challenges and efforts taken to face them in Chile as a case study and in other similar settings in general. This research determines whether current practices can or cannot deal with the water and energy challenges investigated. This research is also essential in international settings to meet the United Nations Sustainable Development Goals (SDGs) specifically “clean water and sanitation” (SDG 6), “affordable and clean energy” (SDG 7),

and “responsible consumption and production (SDG 12)”. Defining the challenges and efforts may meet the affordable and clean energy, decent work and economic growth, infrastructure, industry and innovation, sustainable consumption and production, and climate action goals.

Thus, in meeting the research contributions, three research questions have been developed as follows.

- (1) What are the water and energy challenges that Chile’s copper mining industry is facing?
- (2) What are the relevant EMIs that the copper mining industry in Chile uses to address the identified challenges?
- (3) How can mining companies benefit from EMIs?
- (4) The results of this research were outlined according to these research questions.

2. Literature Review

2.1. The Mining Industry in Chile

There are various challenges that the mining industry in Chile needs to deal with. One is the atmospheric pollution caused by the smelting processes. Mining companies have invested significant money to improve emission control technologies and reduce their annual emissions, especially sulphur dioxide and arsenic [17]. Another pertinent issue is the impact on land use. The various landscape modifications caused by mining operations, erosion, and soil pollution can adversely affect human health and biodiversity.

In this regard, due to current legislation through the environmental evaluation system in Chile, companies must present an adequate closure plan for the mining operation, in which all stakeholders must participate, and new projects cannot be approved without this closure plan [17,18]. However, in Chile, water availability is one of the most critical challenges that the mining industry must face since it is not directly dependent on the actions that companies can develop. Hence, they should find the solution with the participation of all stakeholders [8,17,19].

Geographically, most mining industries are in the country’s north, with a high water risk due to competition for water use among various stakeholders. Additionally, various water pollution problems have occurred in an area caused by a lack of environmental regulations before 1994. Besides water competitiveness and pollution problems, there is also a lack of rainfall in the zone, an issue caused by climate change that has affected the whole country [8].

Energy challenges, like water, are highly relevant for the Chilean mining industries since there is a high dependence on the national energy distribution system, which they do not control. The energy matrix system in Chile mainly uses fossil fuels, including oil and natural gas, which are not available in the country and must be imported [13,17]. Moreover, hydroelectric energy has significant relevance in the energy power generation in Chile. If there is extreme drought, such as the one that occurred in 2007, there could be a reduction plan in using electricity during that year [17].

The industry is searching for more sustainable practices to address significant challenges concerning water resources and high energy consumption rates [20]. Water, a critical resource for the copper mining industry, is used in many stages of the mining process [21]. Based on projections, total water consumption for copper mining in Chile will be 23.3 (m³/s) by 2031, representing an annual average increment of 2.1% [22].

The increase in water consumption is due to two main reasons. The first is a change in the production matrix because of an increase in the treatment of sulphide minerals. Sulphide minerals must be processed through flotation, which requires a much more intensive process in using water than oxide minerals. The second reason is a drop in ore grade. Because of that, the extraction process requires processing a more significant amount of minerals to obtain a ton of acceptable copper [22]. Indeed, energy consumption will rise around 33.6% by 2031, representing a 3.05% annual increase [23].

Many factors influence the need for mining companies to improve their efficiencies, such as a decrease in ore grade, an increment in energy costs, water conflict between different stakeholders, or water scarcity. In these cases, water and energy challenges are a relevant concern for the mining industry in Chile because of the need to reduce water consumption and boost the electricity generation capacity to ensure sustainable operation [22,23].

2.2. Sustainability Effort

Companies have developed EMIs to address the distinct challenges. EMIs are local environmental management plans that tackle environmental risks in Chile [24]. In this regard, understanding the dominant EMIs is necessary to provide enough information for the mining industry to help them make informed decisions regarding future projects [14]. Evidence showed that sustainable development in the mining industry had aided economic growth in Chile and other countries where mining plays a crucial role. However, there are different aspects that companies must be aware of to achieve sustainable operations [17].

In this context, the Social License to Operate (SLO) is currently a relevant, sustainable aspect that Chilean mining companies should consider when planning and managing water- and energy-related strategies. Conflicts with stakeholders can lead to community distrust and lawsuits, resulting in high additional costs for mining companies' operations [25]. The SLO is a primary concern for mining companies because during the decision-making process for a new project, when the environmental evaluation is completed, there is a citizen participation process in which different stakeholders can participate in reviewing environmental studies and presenting observations regarding the project [26].

The mining industry must develop sustainable strategies that benefit both companies' productivity and the various stakeholders who play an essential role in ensuring local sustainability to avoid conflict and reduce social and environmental issues. Companies that use environmental management strategies can face many relevant aspects which can affect society negatively. Water and energy concerns are relevant current challenges for Chile's mining industry [17].

Sustainable development is relevant for other mining countries, and some researchers have conducted studies on the subject. For instance, in Finland, water is one of the critical challenges identified in the mining industry [27]. The government develops a strategy to address it and other challenges [3]. This plan considers sustainable water balance management, recirculation systems, and energy efficiency strategies [3].

Even though companies reported sustainable practices, the information still limits the ability to evaluate their actual effectiveness [3]. Companies have applied sustainable water strategies since the 1970s to ensure water availability for industrial processes. Nonetheless, it is still critical for the mining industry due to the constant water requirement and competition among stakeholders [28].

In this sense, the primary aim of most South African mining companies is to reduce water consumption [29]. Water recirculation and reuse systems are EMIs that can reduce water consumption and have been applied in several mining operations [27–31]. Another alternative is to use seawater and desalination processes, which have been applied by many mining companies in countries such as Australia, Chile, Peru, and Poland [28,32–34].

Furthermore, multiple companies have adopted diverse energy-related strategies. For instance, half of the mining companies in Catalonia, Spain have implemented EMIs to minimise and control energy source consumption [35]. In Colombia, water, energy use, and GHG emissions are critical challenges from the environmental perspective of sustainability. In this regard, mining companies in both countries recognise that renewable energy sources can improve environmental performance [36].

Meanwhile, some mining operations have recovered heat from generators in northern Canada to keep buildings warm [31]. Canadian mining companies have implemented other relevant EMIs such as Ventilation on Demand (VOD) for underground operations, process optimisation through improved monitoring of energy usage, and the use of Non-Conventional Renewable Energy (NCRE), among others [31,37]. In this perspective, solar energy is one of the most acknowledged strategies to reduce fossil fuel dependency. Additionally, solar energy reduces GHG emissions, environmental impacts, operational costs and can generate long-term energy savings [13,31,38,39].

Another aspect that drives sustainable development is innovation and new technology. Indeed, both are essential to keep a company's continuous improvement [40,41]. During the life cycle stages of a mining project, researchers widely study the technology and innovation strategies for energy challenges. However, there are still challenges and research gaps to be filled, such as energy-saving technology and the use of renewable energy sources [40]. An example of innovative technology used in Canada is electric mining equipment, such as Load Haul Dump (LHD). Using electrical equipment can reduce energy consumption in underground ventilation systems by around 40% because of the drop in combustion gases and particles [42].

3. Materials and Methods

3.1. Scope of the Study, Data, and Method

The present article is a semi-systematic literature review which was divided into two parts. The first part used the most relevant literature on the studied topics (Table 1) to explore the water and energy challenges that Chile's mining copper industry faces (Sections 4.1–4.3). The second part of the review explored the EMIs performed by mining companies and how they relate to the challenges identified (Sections 4.4, 4.4.1 and 4.4.2). The last section discussed how mining companies dealt with hydric and energy issues and the benefits of implementing different EMIs (Sections 5.1 and 5.2). The purpose is to understand better the methods used to tackle water and energy challenges in Chile's mining industry. This study can be an international reference due to the importance of Chilean copper mining around the world.

The data used in this research were from mining companies' sustainability reports, progress reports on the cooperation agreement between the ministry of energy and the mining council, official reports from the Chilean Copper Commission (COCHILCO), and mining companies' official websites. This study also used secondary data from the company's sustainable practices review [3]. The aim was to explore and analyse the available secondary data to compile the most remarkable sustainability practices (i.e., EMIs) from the water and energy perspectives.

After identifying the energy and water challenges, this research evaluated the relationship between those challenges and the EMIs implemented by Chilean mining copper organisations. There are some limitations identified in using secondary data, such as differences in reporting methods and strategies which companies can use [3]. It occurred when companies with global operations, such as Broken Hill Propriety Company Ltd. (BHP), used a different disclosure method than a local organisation such as CODELCO. As the data used to review the EMIs were from copper mining companies operating in Chile, the findings and results may be limited to similar operating conditions or challenges related to the perspectives studied.

Therefore, this study developed two main phases. The first was to generate the research questions that were directly related to the article's main topics. Subsequently, these research questions developed a structured search based on various keywords related to the subject studied.

3.2. Database Selection

After formulating the research questions, database sources were selected to search for articles and documents. The selected database sources were Web of Science and Google Scholar, as both have many resources that can be used in different studies [43,44]. Following the selection of search engines, it was necessary to use the keywords chosen to answer the research questions. These terms were used to study various research articles, review papers, official national and technical reports, and mining companies' reports (mainly sustainability reports and, for some companies, integrated reports, such as BHP). Sustainability reports and integrated reports both are essential for the research since organisations annually present their progress in the sustainability area through these reports. The keywords used have a direct relationship with the topic discussed, which are: "water mining Chile", "environmental management mining Chile", "sustainable strategies mining Chile", "mining sustainability Chile", "sustainable initiatives mining Chile", "better practices mining Chile", "energy mining Chile", "water challenge for mining Chile", and "energy challenge for mining Chile". The years considered for this research were between 2010 and June 2021.

Initially, 524 documents were identified. After analysing the titles of each article, summaries, and searching for critical concepts related to the topic studied, 29 academic articles were selected (see Table 1) to develop the study on water and energy challenges in Chilean mining, exploring the current state of EMIs developed by mining companies. For more information on the literature included, see Appendix A.

Table 1. The most relevant literature regarding the study topics.

| Topic | Relevant Aspects | Authors |
|-------------------------------------|--|---------|
| Environmental management strategies | Evidence regarding the use of seawater in mining with an emphasis on its use in Chile. | [9] |
| | Relevance of water-related data disclosures presented in corporate sustainability reports. Use the water footprint as a tool to standardise the impact associated with the mining process. | [45] |
| | Potential water supply solution to an integrated system. One relevant alternative is to improve the recirculation water system from tailings storage. | [46] |
| | Assessment of water risk and the climate change exposition. Relevance of the resilience that mining companies need to create. | [10] |
| | A review of sustainable development in the Chilean mining industry: past, present, and future. | [17] |
| | Diverse and sustainable strategies for the Chilean mining industry through a local model according to the region. | [26] |
| | Diverse study cases regarding sustainable practices and efficient use of water in the mining industry. | [7] |
| | Innovation as a drive to keep the competitiveness in the mining industry in Chile, and the need to encourage public-private partnerships. | [47] |
| | A study regarding the minerals industry's response to sustainable development in waste disposal. | [48] |
| | Discussion for diverse issues and drivers to implement solar technologies in the mining industry in Chile. | [13] |
| | A study of Life Cycle Assessment (LCA) regarding the impact of energy production and the analysis of the integration of solar technologies. | [12] |
| | This research compares and studies the corporate-sponsored community development and social legitimacy of two mining operations as a study of cases in Chile. | [25] |
| | A study of solar thermal technologies. | [49] |

Table 1. Cont.

| Topic | Relevant Aspects | Authors |
|-----------------------------|--|---------|
| Mining sector in Chile | This work presents a multi-objective optimisation approach to designing integrated water supply systems for the mining industry. | [50] |
| | Potential model to predict copper demand which evaluates challenges of the industry such as ore grades, energy and water consumptions, GHG emissions, and generation and disposal of tailings. | [51] |
| | Cost analysis regarding water consumption and diverse alternatives. | [52] |
| Water and energy challenges | Lack of water in the northern territory in Chile and desalination plants can be an alternative to supplying water. | [32] |
| | Problems regarding water scarcity and sustainability, which generate the conflict between diverse stakeholders regarding water access. | [53] |
| | Information about the decline of the copper ore grade, which will continue. Thus, because of the ore grade reduction, the energy requirements will increase. | [54] |
| | Study regarding water conflict between different stakeholders and the lack of water availability. | [20] |
| | Study regarding mining and glaciers. | [55] |
| | Scientific evidence about glacier changes and the conflict because of the Pascua Lama mining project. | [56] |
| | Two industries that generate a decline in water quality in Elqui River are the mining and agriculture industry—Water Quality Assessment. | [57] |
| | Different legal problems related to conflicts between different stakeholders because of the use of water. | [58] |
| | Proofs that climate change, and mining activity, can put these water sources at risk. | [59] |
| | Study of glaciers and the sustainability issues with mining operations. | [60] |
| | Water conflict between diverse stakeholders, especially mining and agricultural industries. An analysis of the water scarcity index for different regions in Chile. | [8] |
| | An analysis of the fossil fuel dependency of the energy system in Chile. | [15] |
| | Impact of the mining industry on settlements and communities, a mining space characterisation. | [5] |

3.3. Analysis of Data

The relationship between challenges and company EMIs and all strategies related to those identified challenges was analysed through content analysis. Content analysis is a systematic method of summarising and computing phenomena [61]. There are five critical steps of content analysis, i.e., (1) understanding the data, (2) focussing the analysis based on the crucial research questions, (3) categorising the data, (4) identifying the patterns and relationships between and within data, and (5) interpreting the data [62]. These methods were implemented to interpret, analyse, and summarise the data. The first data analysis involved the water and energy challenges the mining copper industry faces in Chile. Next, the second analysis explored the EMIs that have been carried out by mining companies and how they associate with the challenges identified. The EMIs conducted by different companies were listed according to each water and energy challenge before the dominant EMIs, and their benefits were evaluated.

4. Results

4.1. Water and Energy Challenges of Chilean Mining Companies

Most copper mining operations are in northern Chile, which is one of the driest areas on the planet, and this factor complicates mining operations constantly. The water shortage causes insufficient resources to meet the region's total demand, generating constant

competition for this resource [8]. Another factor is the scarcity of water rights in the north. In Chile, any company that needs to use surface or underground water must have a water right. There are various water rights (expressed in m^3/s) that allow the use of continental water. However, most of them are consumptive rights in the northern region that allow the owner to consume the water without restoring it [63].

The agricultural sector consumes the most water at the national level, accounting for 82% (around $527 \text{ m}^3/\text{s}$), while the mining industry consumes 3.1% (around $20 \text{ m}^3/\text{s}$), but the scenario varies by region. The agricultural sector of the northern region occupies 71.8%, followed by the mining industry at 14.5%, generating constant competition for water consumption between both sectors. Although the mining industry is the second-largest consumer of water in Chile's northern region, it recycles a significant portion of the water it uses; thus, its consumptive water use is lower than its total requirement [63]. In fact, by 2019, the copper mining industry used $69.83 \text{ m}^3/\text{s}$, with recycling water accounting for 53.07% of the total, implying that only 46.93% is related to water consumption.

Energy is another necessary supply for mining companies because of the diverse production and beneficiation processes [64]. By 2019, the copper mining industry consumed approximately 175,134 TJ, or 14% of total energy in Chile, with 51.3% and 48.7% being electricity and fuel, respectively. Energy consumptions by the mining copper industry have not followed the same pattern over the years. Despite an increase of nearly 100% between 2001 and 2019, energy consumption has decreased in two years. In 2010, it fell around 2.4% compared to 2009, and in 2019, 0.91% compared to 2018. The principal reason for both diminishing energy consumption is a reduction in copper production between 2010 and 2019, which is directly related to the energy consumed by mining companies [65].

The projection shows that the demand for water and energy will increase for copper production over time, posing challenges for the industry's ability to remain competitive. Another factor that could increase stress is climate change, linked to an increase in the median annual temperature, resulting in faster melting glaciers and less water stored in the mountains [66]. Another aspect is the decrease in copper ore and the ageing of deposits, increasing electrical energy consumption by 34% over the next ten years. The copper mining industry must develop new strategies to address all issues, such as enhancing energy efficiency and encouraging NCRE to maintain the industry's competitiveness [67].

4.2. Water Challenges

The northern area of Chile has the most significant number of mining companies; however, it is also a zone of water scarcity due to a lack of available water for processing all mineral resources [17]. Water scarcity has generated a struggle for this resource between diverse stakeholders, including the agricultural sector and neighbouring communities, where the trend in increasing water requirements for processing minerals has significant implications for current and future production because there are risks associated with the competitiveness of water consumption [53]. The reduction in water availability in different regions of Chile's northern area illustrates the zone's water scarcity. For instance, between 2009 and 2013, regional average flows in Chile's first region decreased by 2652 L/s , associated with a rainfall reduction because of climate change [8].

Glaciers are another concern because Chile has approximately $24,000 \text{ km}^2$ of glaciers, representing approximately 82% of the total in South America. At least 5% of the total glaciers are located between the country's centre and north, supporting the regions, especially for its semi-arid zone [68]. Glaciers in Chile are an essential water source for the semi-arid zone (between the south Atacama and the north of the Valparaíso region). However, there is proof that climate change and mining activity can jeopardise these water sources [59]. The "Pascua-Lama" project is an example of glacier destruction, whereby the national authority allowed Barrick Gold Corporation to remove around 0.2 km^2 of rock glaciers between 2001 and 2006. Instead, they destroyed over 60% of the rock glaciers in the mining area [55,56]. In this project, the Barrick company had invested more than USD

3.000 million by 2013. However, because of the glacier's destruction that was provoked, in 2018 the company had to suspend the project in Chile and begin the closure plan [56].

Enhancing the operational processes to reduce water pollution is another challenge for the mining industry [17]. Water quality could be harmful due to the effects mining operations can cause in ecosystems [17]. This point is critical for the sustainability challenges because poor management of resources can harm the environment and communities while also generating extra expenses for companies. Additionally, suppose companies do not collaborate with stakeholders (e.g., communities and local government) to ensure adequate water quality. In that case, they risk losing the trust of communities and the SLO [69].

Following the exposure of diverse critical aspects related to water challenges in the copper mining industry in Chile in previous sections, it is possible to propose five main water challenges identified which companies need to address. Those challenges are water scarcity, collaboration with stakeholders in hydric aspects, improving glacier management, reducing water pollution, and ensuring water quality.

4.3. Energy Challenges

The past sections discussed the high level of energy consumption, especially electricity, where the mining industry accounted for around 37% of Chile's total consumption [70]. This aspect generates significant economic concern for companies, given that Chile's energy costs are higher than other mining operation countries. Companies must reduce their electricity costs, a critical challenge to remain competitive in Chile's copper mining industry. The principal reason for this high cost is the volatility of fossil fuel prices, such as oil, because Chile imported most of them. They are the primary source of energy production, accounting for approximately 87% of total production [14]. Figure 1 shows that Chile's energy costs were higher compared to other mining countries by 2010. For instance, Chile had an energy cost of around 12.3 c/kWh (cents per kWh), while Australia had a cost of less than 8 c/kWh (i.e., 35% less) [14].

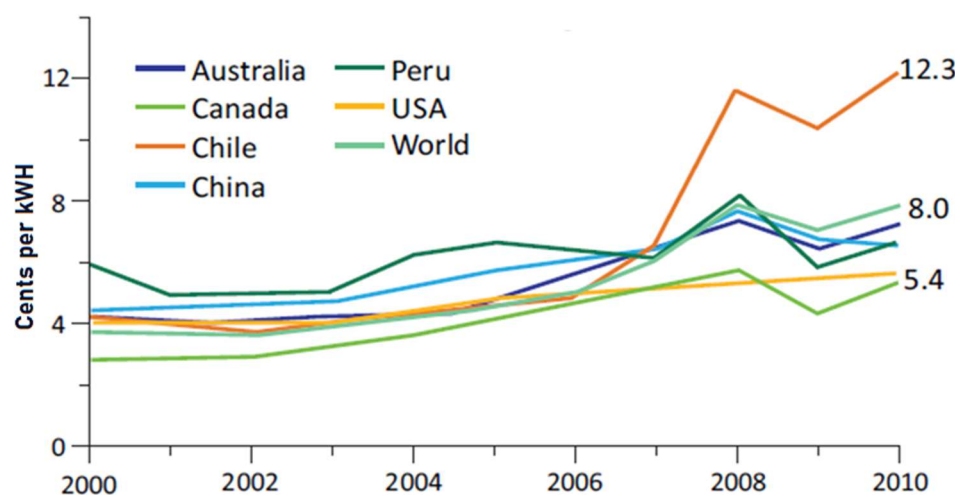


Figure 1. The energy costs for some mining countries in the world. Reproduced with permission from CSIRO Chile, *The Future of Mining in Chile*; published by CSIRO, 2014 [14].

The mining industry's energy consumption will increase due to the diminishing in the ore grade. This issue generates an increment in the extraction cost. Because of the reduction in copper in the mineral deposits, companies need to process more rock minerals to obtain the same copper [54,70]. Another reason related to the energy consumption increment is Chilean copper mining companies using more seawater. Desalination plants are an alternative for companies because of the water scarcity in Chile's northern regions. However, there are some aspects that companies must analyse/consider before implementing them.

The fundamental aspect is the operational cost, which is related to energy consumption. The energy demand by the desalination process is high, which includes pumping water from the coast [9]. The distances that seawater needs to be pumped are significant, usually around 1000 m above sea level. Moreover, considering the latest projections, which indicate that the use of seawater will increase, it represents a critical concern in terms of operational costs [20,22]. Figure 2 shows the different costs of using seawater for various mining nations. It is possible to see that the highest cost is in Chile. The figure also depicts that the cost of seawater in Chile is 218% more expensive than freshwater [54,71].

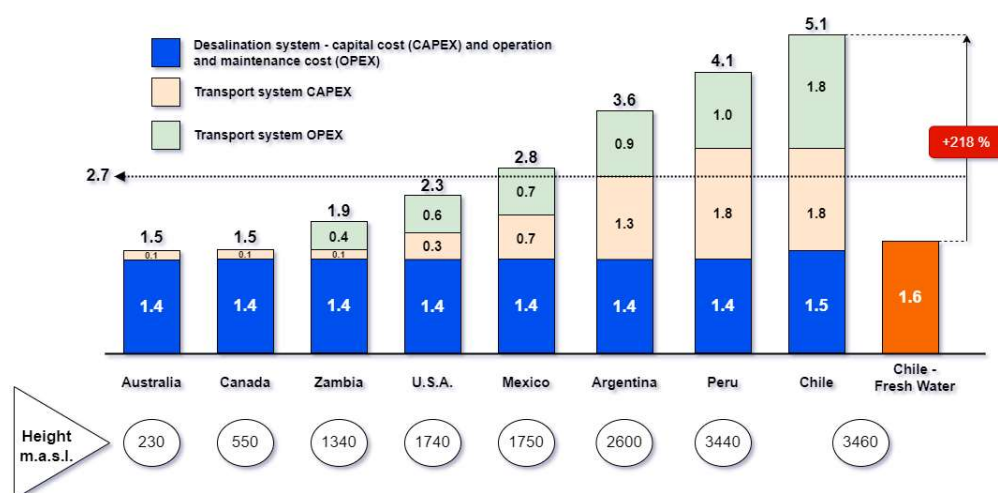


Figure 2. The cost (USD/m³) of using seawater for different countries [71].

Another factor is the high dependency that the electricity interconnected systems have on fossil fuels, which are Sistema Interconectado del Norte Grande (SING) in Spanish and Sistema Interconectado Central (SINC). Both systems were combined in 2017, creating a new interconnected system called Sistema Eléctrico Nacional (SEN) [65]. However, it still has a high fossil fuel dependency, particularly coal, which, if nothing changes in Chile's energy matrix, will increase the GHG emissions [72]. By 2015, the SING and SINC had around 20,141 MW, with coal, diesel, fuel oil, and natural gas accounting for 11,707 MW, or 58.12% of the total installed capacity. However, only in the SING, which is close to most copper mining companies, in the same type of fossil fuel generation's energy process, the installed capacity represents around 94.55% of the total by 2015 [15]. The mining industry should reduce its energy consumption by improving energy efficiency and changing the dependency on fossil fuels to NCRE [73].

According to the previous analysis, there is more than one energy challenge that the copper mining industry in Chile needs to address. However, it is possible to propose five main energy challenges that companies could face. These challenges are: reduce energy consumption and costs, improve energy efficiency, and reduce fossil fuel dependency and climate change.

4.4. Initiatives Taken by the Companies to Address Water and Energy Challenges

4.4.1. Initiatives for Water Challenges

The following section analyses the EMIs for different companies according to each identified challenge.

Anglo American

The company developed a Water Management System (WMS) according to the International Council on Mining and Metals (ICMM). This development has allowed the company to reduce water consumption in 2017 by 1.4 million m³ less than in 2016 [74]. Concerning water stakeholder conflicts, Anglo American has a tool called Socio-Economic Assessment Toolbox (SEAT), by which they work with communities in catchment areas

to improve water quality monitoring [75]. The Soldado mining operation has allied with the Nogales Commune to improve the WMS and reduce stakeholder conflict [76]. Another initiative is coarse particle flotation (CPF); this technology increases the grinding size with the same mineral recoveries, reducing water consumption by around 20% [77]. The Bronces mine implemented a Water Recirculation System (WRS), recovering water from the concentrator plant by recycling it through the tailings dam and pumping it to the grinding process, recycling over 78% of the water [74]. They ran a water balance through a stochastic model to project the variability and availability of this resource [74]. The company has collaborated with the community to improve the rural water system in Chacabuco to ensure better infrastructure and availability [77].

Doña Inés de Collahuasi

The company used a Risk Management Cycle (RMC) tool to ensure sustainable water consumption, including a water extraction monitoring system [78]. The WRS of the company is working on tailings thickening, allowing using less water in the tailings, achieving a recirculation of around 76.7% by 2017 [79]. The company has developed some pilot tests using the Thickened Tailing Disposal (TTD) technology, which can help to reduce the percentage of water in tailings [80]. In addition, Collahuasi is developing a project to enhance drinking water and irrigation systems for communities under the influence [79,81].

The company has a project which will incorporate a seawater desalination plant. With a capacity of 1050 L/s, the plant expects to reduce by 70% the water extraction rates from the water basin. The company expects by 2025 that 2/3 of the water that Collahuasi uses will come from desalination process [81].

Antofagasta Minerals

The company has programs in place where they work with communities, ensuring water availability. For instance, in the program “Somos Choapa”, they helped local communities to improve their drinking water quality [82]. The organisation has a WMS, where the focus is working with stakeholders and ensuring efficient water consumption, generating a rate of water recirculation between 80% and 96% [83,84]. They also carried out a monitoring plan to ensure water quality in nearby zones [82]. For all the operation, Antofagasta Minerals used around 53% of total seawater, whereas Antucoya used 100% without desalination [83,85]. Centinela used around 90%, where most of which was obtained without the desalination process. In contrast, Zaldivar and Los Pelambres were both using continental water [86]. Concerning glaciers, the company has implemented a pilot project with Glacier Coolers, seeking to reduce the melting process using removable covers [83].

For the Centinela mine, they had applied TTD technology, increasing the percentages of solids in the tailings to around 65% [82]. In the Los Pelambres mining operation, the company is developing research about a new treatment for acidic water by natural and alternative systems, allowing the organisation to define a long-term sustainable treatment system [84]. The expansion plan INCO in Pelambres considers the construction of a new desalination plant with a capacity of 400 L/s by 2020. This plant will increase its capacity until 800 L/s by 2025 and the seawater use for all the company will account for nearly 90% of total water consumption in 2025 [85,86].

BHP Chile

BHP Chile has three operations which are Escondida, Cerro Colorado, and Spence. Concerning water management, the organisation has a WMS aligning to the ICMM's sustainability framework, and it includes a Water Report that presents the water balance for all its operations [87,88]. For BHP, in all of Chile's mining operations, 87% of the water is from the sea [89]. With the Escondida mine, in 2018, the company inaugurated the largest desalination plant in South America (EWS), with a capacity of 2500 L/s. The system includes 180 km of pipeline that must transport water 3200 m above sea level. Moreover, this plant is in the company's plan to end groundwater extraction by 2030 [88,89]. The Cerro Colorado mine has implemented a wetland management plan, which includes a monitoring plan. This initiative aims to recover the aquifer, ensuring ecology flow and regulatory compliance [87]. Concerning the Spence mine, the company is expanding this

operation by building a new desalination plant with a capacity of 1000 L/s to ensure water availability [87]. The desalination plant began its operations in the last part of 2021, seeking to ensure water availability for the Spence Growth Option (SGO) project, which would increment the annual copper production by 185 Kt [89].

CODELCO

CODELCO, the Chilean state-owned copper mining company, has six extractive mines: Radomiro Tomic, Chuquicamata, Ministro Hales, Gabriela Mistral (Gaby), Salvador, Andina, and Teniente [90]. The company had developed a Sustainability Master Plan. The Sustainability Master Plan is used to manage an environmental risk system with a WMS to ensure efficient use and a 10% reduction in freshwater consumption [91]. The organisation created a monitoring program for all their hydric sources. The company had an average of 77.3% water recirculation by 2018, while Radomiro Tomic had achieved 89.9% [90]. Water recirculation has occurred at different stages, mainly from the tailings [90].

The company is considering building a desalination plant (800 L/s) with a 160-km-long piping system to supply water to the northern operations. By 2020, the company targets to have changed some of the contracts awarded to begin the construction [91]. Andina changed the current open pit to avoid glaciers' destruction by not exploiting the zone close to the glaciers [90]. Regarding community support, Andina had developed projects to enhance drinking water availability in some communities near the mine [90]. At the Teniente mine, the company studied an instrumentation plan to monitor more efficient water consumption [92]. In addition, in the Radomiro Tomic mining operation, the organisation implemented an innovation system on the dynamic leach piles. A Thermo-film can save up to 80% of the water used to leach [93]. With the new project of Radomiro Tomic, the company considered using TTD technology to ensure a high rate of water reuse [92]. Finally, in the Salvador mine, the company was developing a new project to work with communities to improve the drinking water infrastructure for nearby communities [94].

Teck Chile

Teck has two mining operations in Chile: Quebrada Blanca and Carmen de Andacollo. The organisation has an Environmental Management System based on ISO 14.001, sustainability indicators, and an integrated risk management structure [95]. The company works with the community to support some improvements in water monitoring, supply, and use. They help foster the efficient consumption of water and enhance the drinking water supply system [96]. A new project, Quebrada Blanca II (QB2), considers seawater to ensure water supply. This new desalination plant will have a maximum capacity of 1300 L/s and supply water 4300 m above sea level [96,97].

Sierra Gorda

Sierra Gorda uses seawater recovered from the cooling operation of a thermoelectric plant in Mejillones, where the water is used without desalination [98]. The company is implementing TTD technology to improve the water recirculation process from the tailing dam [98].

Table 2 summarises each EMI by the organisation, along with the benefits and water challenges described in the previous sections. The initiatives are classified into similar groups, such as WM system, community strategic plan, and seawater use.

In addition, Table 3 shows a resume regarding the water consumption for each mining operation, water reuse, and recycling percentages, the specific main Environmental Management Initiatives to face water challenges detected and their benefits.

Table 2. Relevant EMIs to deal with water challenges.

| Organisation | Operation | Environmental Management Initiatives | Water Scarcity | Collaboration with Stakeholders in Hydric Aspects | Improve Glaciers' Management | Water Pollution | Water Quality |
|----------------------|----------------|--|----------------|---|------------------------------|-----------------|---------------|
| Anglo American | All operations | WM system | ✓ | - | - | ✓ | ✓ |
| | | Application SEAT | - | ✓ | - | ✓ | ✓ |
| | El Soldado | Community strategic plan | ✓ | ✓ | - | - | ✓ |
| | | Coarse particle flotation (CPF) | ✓ | - | - | - | - |
| | Los Bronces | Water recirculation system | ✓ | - | - | ✓ | - |
| | | Water balance | ✓ | - | - | - | ✓ |
| | | Improvement in a rural water system | ✓ | ✓ | - | - | ✓ |
| Collahuasi | Collahuasi | WM system | ✓ | - | - | ✓ | ✓ |
| | | Water recirculation system | ✓ | - | - | ✓ | - |
| | | Community strategic plan | ✓ | ✓ | - | ✓ | ✓ |
| | | Seawater use | ✓ | ✓ | - | ✓ | ✓ |
| Antofagasta Minerals | All operations | Community strategic plan | ✓ | ✓ | - | ✓ | ✓ |
| | | WM system | ✓ | - | - | ✓ | ✓ |
| | | Water balance | ✓ | - | - | - | ✓ |
| | | Monitoring quality of water | - | ✓ | - | ✓ | ✓ |
| | | Water recirculation system | ✓ | - | - | ✓ | - |
| | | A pilot project to protect glaciers | - | - | ✓ | - | - |
| | Antucoya | Seawater use | ✓ | ✓ | - | ✓ | ✓ |
| | Centinela | Seawater use | ✓ | ✓ | - | ✓ | ✓ |
| | | Thickened tailings technology | ✓ | - | - | ✓ | - |
| | Los Pelambres | Research new treatment of acidic water | - | - | - | ✓ | ✓ |
| | | Seawater use—project | ✓ | ✓ | - | ✓ | ✓ |
| BHP Chile | All operations | WM system | ✓ | - | - | ✓ | ✓ |
| | | Water balance | ✓ | - | - | - | ✓ |
| | | Monitoring quality of water | - | ✓ | - | ✓ | ✓ |
| | Escondida | Seawater use | ✓ | ✓ | - | ✓ | ✓ |
| | Cerro Colorado | Wetland recovery | ✓ | ✓ | - | - | - |
| | Spence | Seawater use—project | ✓ | ✓ | - | ✓ | ✓ |
| CODELCO | All operations | Environmental risks management system | ✓ | - | - | ✓ | ✓ |
| | | Monitoring quality of water | - | ✓ | - | ✓ | ✓ |
| | | Water recirculation system | ✓ | - | - | ✓ | - |
| | | Seawater use—project | ✓ | ✓ | - | ✓ | ✓ |
| | Andina | Modification of current open pit | - | ✓ | ✓ | - | - |
| | | Community strategic plan | ✓ | ✓ | - | ✓ | ✓ |
| | Salvador | Community strategic plan | ✓ | ✓ | - | ✓ | ✓ |
| | Radomiro Tomic | Use of thermal film—water reduction | ✓ | - | - | - | - |
| | | Thickened tailings technology—project | ✓ | - | - | ✓ | - |

Table 2. Cont.

| Organisation | Operation | Environmental Management Initiatives | Water Scarcity | Collaboration with Stakeholders in Hydric Aspects | Improve Glaciers' Management | Water Pollution | Water Quality |
|--------------------|-----------------|---|----------------|---|------------------------------|-----------------|---------------|
| Teck Chile | All operations | Environmental Management System | ✓ | - | - | ✓ | ✓ |
| | | Community strategic plan | ✓ | ✓ | - | ✓ | ✓ |
| | Quebrada Blanca | Seawater use—project | ✓ | ✓ | - | ✓ | ✓ |
| KGHM International | Sierra Gorda | Seawater use without desalination process | ✓ | ✓ | - | ✓ | ✓ |
| | | Thickened tailings technology—project | ✓ | - | - | ✓ | - |

Environmental Management Initiatives which help deal with water challenges have been marked with ✓.

Table 3. Total water consumption and the main EMIs to deal with water challenges for each mining operation and their associated benefits.

| Operation | Continental Water (Millions of m ³) ¹ | Seawater (Millions of m ³) ¹ | Total Water Use (Millions of m ³) ¹ | Water Reuse | The Main EMIs to Face Water Challenges Detected | Benefits Associated to EMIs |
|---------------------------------------|--|---|--|-------------|---|---|
| Anglo American. All global operations | 34.24 | - | 34.24 | 89% | Work with communities and authorities program. | Reduction in water conflicts with stakeholders—enhance the relationship. |
| | | | | | Water Management System. | By 2017 1.4 million m ³ less than in 2017. |
| Anglo American, El Soldado | 6.56 | - | 6.56 | 80% | Coarse particle flotation (CPF). | It is expected to save around 20% of water consumption. |
| Anglo American, Los Bronces | 26.5 | - | 26.54 | 85% | Improvement in a rural water system. | In 2020, water availability for communities incremented by 20%. |
| | | | | | Recirculation System from concentrator plant to grinding process—pumping system. | Reduction in water consumption was around 48% by 2013. |
| Anglo American, Chagres | 1.14 | - | 1.14 | 99% | - | - |
| Collahuasi | 33 | - | 33.17 | 76.7% | A new project of a desalination plant. | By 2025, it expects to reduce by 70% the water extraction rates from the water basin. |
| | | | | | TTD technology | To reduce the percentage of water in tailings. |
| | | | | | Project to enhance drinking water and irrigation systems for communities under the influence. | 14 Km of irrigation canals for communities, reducing water conflicts with diverse stakeholders. |
| | | | | | Community strategic plan. | Reduction in water conflicts with stakeholders—enhance the relationship. |

Table 3. Cont.

| Operation | Continental Water (Millions of m ³) ¹ | Seawater (Millions of m ³) ¹ | Total Water Use (Millions of m ³) ¹ | Water Reuse | The Main EMIs to Face Water Challenges Detected | Benefits Associated to EMIs |
|---|--|---|--|-------------|--|--|
| Antofagasta Minerals, all global operations | 30.6 | 34.7 | 65.4 | 80–96% | The seawater as the focus for reducing continental water use. | The seawater use will account for 90% of total water consumption in 2025. It helps to reduce the hydric stress and conflict with water rights. |
| | | | | | Community strategic plan. | Reduction in water conflicts with stakeholders—enhance the relationship. |
| Antofagasta Minerals, Antucoya | 0.0 | 5.8 | 5.78 | - | Seawater use. Antucoya uses 100% without desalination for all the operation. | Reduce the hydric stress and conflict with water rights. |
| Antofagasta Minerals, Centinela | 2.7 | 29.0 | 31.62 | - | Seawater—around 90% from desalination process. | Reduce the hydric stress and conflict with water rights. |
| | | | | | TTD technology | Increase the percentages of solids in the tailings to around 65%, reducing water consumption in the tailing dam. |
| Antofagasta Minerals, Los Pelambres | 21.2 | - | 21.25 | - | Desalination plant with a capacity of 800 L/s by 2025. | Reduction to 100% of the use of continental water and the dependency of water rights. |
| | | | | | The project “Somos Choapa” with local communities. | Enhanced water access for communities under the influence—34 Km of irrigation canals for communities. Reduction in water conflicts with stakeholders—enhance the relationship. |
| | | | | | Research a new treatment of acidic water. | Define a long-term sustainable treatment system—competitive advantages. |
| Antofagasta Minerals, Zaldivar | 6.7 | - | 6.72 | - | - | - |
| BHP, Global all operation | 14.4 | 96.7 | 111.2 | - | Management system based on water stewardship framework from ICM. | Risk identification and associated action plans. |
| | | | | | Water balance for all operations in Chile. | To improve stakeholder collaborations and transparency. |
| | | | | | Monitoring systems in diverse points. | Reduction in water conflicts with stakeholders—ensure no polluted water, avoid fines. |
| BHP, Escondida | 3.9 | 96.7 | 100.68 | - | Seawater use—two desalination plants—one of the largest in South America 2500 L/s. | Reduction in superficial and/or underground water consumption—ensuring water availability and reducing problem with water rights. |
| BHP, Cerro Colorado | 4.1 | - | 4.07 | - | To recover an aquifer, ensuring the ecology flow. | Reduction in water conflicts with stakeholders—enhance the relationship. |
| BHP, Spence | 6.4 | - | 6.41 | - | Seawater use. Project to build a new desalination plant, 1000 L/s. | Reduction in superficial and/or underground water consumption—ensuring water availability for the expansion project. |

Table 3. Cont.

| Operation | Continental Water (Millions of m ³) ¹ | Seawater (Millions of m ³) ¹ | Total Water Use (Millions of m ³) ¹ | Water Reuse | The Main EMIs to Face Water Challenges Detected | Benefits Associated to EMIs |
|--------------------------------|--|---|--|-------------|---|--|
| CODELCO, all global operations | 186.4 | - | 186.4 | 76.9% | WM strategy to ensure efficient use of the hydric resources. | Plan strategies to reduce 10% of freshwater consumption. |
| | | | | | Monitoring systems in diverse extraction points. | Reduction in water conflicts with stakeholders—ensure no polluted water, avoid fines. |
| | | | | | Project to build a new desalination plant, 800 L/s to supply water to the northern operations. | Reduction in freshwater consumption—ensuring water availability. |
| CODELCO, Teniente | 59.6 | - | 59.65 | - | - | - |
| CODELCO, Chuquicamata | 65.3 | - | 65.30 | 87% | - | - |
| CODELCO, Gaby | 5.9 | - | 5.90 | 87% | - | - |
| CODELCO, Andina | 25.9 | - | 25.88 | | Modification of the current open-pit mine—moving it to another area. | To avoid the destruction of glaciers—ensuring a sustainable operation and avoid fines. |
| | | | | | Improvement in the rural drinking water system for some communities. | Reduction in water conflicts with stakeholders—enhance the relationship. |
| CODELCO, Salvador | 20.2 | - | 20.17 | - | | |
| CODELCO, Radomiro Tomic | 9.5 | - | 9.50 | 90% | Use of thermal film on the dynamic leach piles. | Save around 70% to 80% of the water used to leach. |
| | | | | | Thickened tailings technology—percentages of solid can reach 67%. | More stable tailings and higher percentages of water recovery. |
| TECK, all global operations | 12.4 | - | 12.4 | - | Cooperation with stakeholders regarding hydric resources. | Improve the water scarcity condition in the area with different stakeholders. |
| TECK, Quebrada Blanca | 1.7 | - | 1.74 | - | Project to build a new desalination plant, 1300 L/s. | Reduction in continental water consumption. |
| TECK, Carmen de Andacollo | 10.7 | - | 10.67 | - | - | - |
| Sierra Gorda | 0.95 | 30.6 | 31.59 | - | The use of seawater, without desalination in its process, from the cooling operation of a thermoelectric plant. | 100% of the total water from the sea—a reduction in hydric stress. |

¹ These data are from to the year 2020. The data for water used by each mining company are from each sustainability report and from the report generated by the mining council of Chile [99].

4.4.2. Initiatives for Energy Challenges

Similarly, to identify the EMIs concerning the described energy challenges, this section examines the strategies of some Chilean copper mining companies.

Anglo American

Anglo American is seeking to improve energy efficiency and reduce GHG emissions by implementing energy and climate change management systems, identifying Key Performance Indicators (KPIs), studying and fostering the incorporation of NCRE, and encouraging innovation [74]. For instance, in Los Bronces, the Energy Management System (EMS) allowed a reduction of around 4.9% in its energy and 4% in its GHG emissions by 2017 through the optimisation of its operations and transportation distances [100]. With the El Soldado mine, the organisation implements a fuel optimisation trial plan to improve energy efficiency in trucks 830 AC (FOK), reducing engine RPM [76].

In the Los Bronces mining operation, Big Data's application helped the company reduce around 3% of the energy consumption. The method used was computational tools that allow the organisation to make better decisions about the operation of the pumps [76]. The company has a pilot floating photovoltaic plant on the Las Tórtolas tailing dam with an installed power of 86 kW. This plant seeks to control evaporation in the tailing deposit while also producing energy [100]. In Los Bronces, a prototype of start/stop for trucks was implemented, which reduced fuel consumption by 0.5% in 2016 [74]. Additionally, they developed a strategy to reduce energy consumption in mining camps using, for example, the light-emitting diode (LED) technology [76].

In Chagres, the copper smelting company applied an energy reduction plan with specific measures, allowing the organisation to reduce 4.4% tons of CO₂ equivalent (tCO₂e) and 6.4% energy consumed by 2017 [76]. One strategy was to modify the control in the cooling tower Baltimore, stopping pumps and fans and adjusting cooling capacity based on thermal demand [76].

The last strategy of the company is in the beginning of 2021 they started an agreement with the electricity generating company. The agreement considers a consumption of up to 3 terawatt-hours (TWh) per year, reducing CO₂ emissions around 70% [101].

Doña Inés de Collahuasi

This company employs an RMC Tool to improve management in energy and climate change aspects. They have implemented distinct elements such as EMS, ISO 50.001:2011, and a GHG management system from ISO 14.064:2013, allowing improved energy consumption. Collahuasi has implemented a platform (Powe Bi) to measure these variables online and enhance data collection [78]. Around 64.5% of the total energy consumption of Collahuasi was from two solar plants and other NCRE sources, and by 2025, 100% of the electrical energy will be from renewable energy because of various agreements [81,102]. They measured the organisation's carbon footprint to encourage GHG reduction [78].

Antofagasta Minerals

Antofagasta Minerals plans to reduce GHG emissions according to a Climate Change Standard through a risk management system. They have sought to change the energy to renewable sources [103]. The company implemented an Efficiency Energy Plan based on ISO 50.001, seeking to improve energy efficiency in different areas [83]. For instance, they used Variable Frequency Drive (VFD) to optimise energy consumption in pump stations [103]. Regarding NCRE, around 21% of the company's total energy comes from NCRE, with Centinela substituting 55% of the diesel consumed with a solar thermal plant [84].

Centinela signed an agreement with Engie Energia Chile SA to supply all of its energy from renewable sources by 2022 [104]. Centinela has worked with the Mine to Mill initiative, which is focused on optimizing different processes of the operation. This strategy analyses the effect of the feed granulometry, where grinding for semi-autogenous mills (SAG) increases their performance to a lower number of coarse particles. In that case, with an optimization of various processes, such as a reduction in specific consumption SAG because of a reduction in the material's granulometry or a specific energy consumption in electrowinning (EW), they have reduced around 58,148 MWh/year of electricity [86,105].

In Los Pelambres, around 59% of the energy consumed comes from renewable sources [84]. This percentage includes an innovative system, a conveyor belt capable of generating energy. The generation is because of the difference in elevation and the negative slope, producing around 10% of the required energy [106]. Additionally, in Los Pelambres, a VFD was installed on one of the impulsion pumps. This strategy represented a saving of 1548 MWh/year of electricity and a reduction of 587 tCO₂e/year in emissions [86]. Another strategy used in Los Pelambres is the optimisation of processes where, with different actions, such as a performance increment of SAG or in the efficiency of the coarse ore transport system, they reduced the electricity consumption around 87,463 MWh/year [105,107].

With the Zaldivar mine, they implemented a project in collaboration with academia called CEADA. They promote biomass research to reduce GHG emissions and generate adaptation for some species in arid zones [103]. Furthermore, Zaldivar signed an agreement with Colbun S.A. (electricity generator and distributor) to produce energy from renewable sources. With this agreement, Zaldivar produces copper using only renewable energy from 2020 [86,105].

In Antucoya, the company has reduced the fuel consumption in the mining haul trucks by a logistic strategy which includes optimization of truck routes, standardizing shifts, and road improvement management. With that strategy, the company has a reduction of 2161 m³ of diesel a year, which is around 6461 tCO₂e/year [86,105]. In addition, the company generated a reduction in the size of ore feed by optimizing its processes, such as increasing the load factor in blasting or the use of the primary crusher. With this optimization, they have achieved an energy saving of 2744 MWh and a reduction in emissions of 1088 tCO₂e per year [107].

BHP Chile

The company has created a management system to identify risks and implement GHG reduction activities [108]. The company updated the Central Kelar for the Escondida mine to provide enough water for the new desalination plant. The fuel used for this energy centre changed from a coal-fired generation plant to a natural gas combined-cycle unit, reducing by around 203,344 tCO₂e per year by 2017 [87]. Currently, they are studying the conversion from diesel to LNG in the SX-EW process's boiler, reducing GHG emissions [108]. Furthermore, they developed a management plan regarding energy efficiency, which includes a manual to standardise criteria. For instance, they use alternating current for copper deposition in the electrowinning process (Hecker Project Cathode), saving around 11 GWh [87].

In Escondida, they made modifications to the design and materials of ball mills. They changed the steel linings to double wave designs of steel-rubber composite material. This energy-efficient strategy allows them to reduce energy consumption between 3 to 5%, which is around 30,000 MWh per year [107,109]. Furthermore, Escondida has signed an agreement with an electricity supplier to ensure a 100% renewable power source. The alliance will start in the middle of 2022 when they seek to reduce their carbon footprint and unit power costs [89]. In a similar way, Spence signed an agreement in 2020 with an electricity supplier which will supply energy from renewable sources from 2022 [89].

Spence made improvements to the EW process by installing anode separators to reduce short circuits and increase current efficiency. In addition, they installed thermographic cameras in the cells for monitoring, where this energy efficiency strategy generated savings of 5% per year in electrical energy in the EW process [109]. In addition, Spence is seeking to change its fleet of Caterpillar 793D and 793C mining trucks to Komatsu 980E electric trucks in search of optimizing its processes. This change of fleet would generate a saving of 7% in fuel for trucks [107,109].

CODELCO

This company has an Environmental Risks Management System, which includes KPIs for energy efficiency and a corporate regulation on the subject for investment projects [90]. Concerning NCRE, CODELCO signed agreements to ensure that around 22.5% of the electric supply in the northern operations will be generated by renewable energy sources [90]. They are testing electric vehicles to transport people while reducing GHG emissions [93]. With Teniente, the company intends to build a run-of-river mini-power plant that will use tailing as an energy source. The material will be deposited into a dam and produce a waterfall during the process using the tailing channel, thus providing around 20,000 MWh/year [110]. By 2019, Teniente had used electric buses and the first hybrid LHD, focusing on electromobility [93]. This hybrid LHD allows a reduction in diesel consumption of over 25% and operational cost of 30% [94].

With Chuquicamata, they developed the first solar energy power plant, which has a capacity of 1.1 MWp and can reduce CO₂ by 1680 tons per year [92]. In addition, Chuquicamata signed an agreement for the electricity supply contract where, at the end of 2021, 80% of the supply came from NCRE [94]. In the underground mine project, they are developing a ventilation system called Ventilation on Demand (VOD), which will operate and distribute the air automatically, allowing the system to adapt to the instant demand, reducing around 20% to 50% of the energy consumed for this concept [93]. In a similar case, the company in the Andina underground mine uses a VOD to manage the ventilation system according to the operation necessity and its automated programs, allowing the evacuation of gases from the blasting process and reducing around 25% of the energy consumed [111].

A solar thermal plant (Pampa Elvira) generates around 5600 MWh annually in the Gaby mining operation. The plant receives energy from the sun, heating a mixture of water and antifreeze, generating thermal energy used in the electrowinning process [92]. This initiative has helped reduce diesel consumption by producing only 20% of the total energy produced by this fossil fuel. As a result, a reduction of around 15,000 tons of CO₂ annually was achieved [93]. Furthermore, one innovative initiative in El Salvador is using hydrogen (H₂) as a catalyst in mining haul trucks' engines, using a hybrid system diesel-H₂, which would reduce costs by 10 to 20% [93].

Teck Chile

Teck has implemented an EMS based on the Towards Sustainable Mining (TSM) initiative [95]. The company targets energy reduction of 2500 TJ and GHG emissions of 275 kilotons of CO₂ equivalent by 2020. They are developing strategies, such as process optimisation and modification of their equipment, which achieve these [112]. In Quebrada Blanca, they signed an agreement with AES Gener, where this supplier provides around 21 MW to the company from a solar plant (Andes Solar), which is 30% of the total energy consumed for Quebrada Blanca, reducing GHG emissions in the company's process [95]. The company signed another agreement with AES for the new project, QB2, to ensure that 50% of total operational needs will come from renewable resources [96,97]. In 2020, Carmen de Andacollo signed a power purchase agreement, ensuring 100% of renewable energy for the operation. Combining both contracts would reduce greenhouse gas emissions by one million tons per year [97].

Furthermore, in the Carmen de Andacollo mine, they implemented a system to optimise the energy consumption in the grinding process through blasting optimisations using a mathematical model and field tests, identifying different hardness in the rock and dividing the explosives accordingly [96]. This modification generates more uniformly sized rocks, reducing the air grooves in the rocks. Additionally, the company will implement some photovoltaic plants to reduce fossil fuel dependency in some processes [113]. Furthermore, Carmen de Andacollo implemented a change in medium to fine liners in the lining of the 20 K Plant cone crushers, without affecting the reliability of the system. This optimization generates a reduction of 4.1 TJ and 471 tCO₂e per year [107]. To reduce the energy used in the grinding process, the company installed a sizer-type crusher. They installed this on the grinding feed line to reduce the grain size of the ore. This optimization generated an energy reduction of 8.9 TJ and 1042 tCO₂e per year [113]. In addition, the company optimized the lifter angle of the SAG mill through the installation of pull-lifter-type systems. This ensures that the grinding pulp moves more easily, reducing electricity consumption by 3% to 4%. A reduction of 12.2 TJ of energy and 1413 tCO₂e per year is estimated [107,113].

Table 4 analyses these initiatives regarding the energy challenges to summarise the most relevant initiatives discussed. The classification of the initiatives is in similar groups, such as energy and climate change management system, optimisation of the process, and use of NCRE, among others.

Table 4. Relevant EMIs to deal with energy challenges.

| Organisation | Operation | Environmental Management Initiatives | Reduction in Energy Consumption | Energy Cost Reduction | Improve Energy Efficiency | Reduce Fossil Fuels Dependency | Climate Change |
|----------------------|----------------|---|---------------------------------|-----------------------|---------------------------|--------------------------------|----------------|
| Anglo American | All operations | Energy and climate change management system | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | NCRE agreements | - | - | - | ✓ | ✓ |
| | El Soldado | Optimisation of processes | ✓ | ✓ | ✓ | - | - |
| | | Optimisation of processes | ✓ | ✓ | ✓ | - | - |
| | Los Bronces | Innovation project | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | Energy efficiency plan | ✓ | ✓ | ✓ | - | - |
| | | Pilot floating photovoltaic | ✓ | ✓ | - | ✓ | ✓ |
| | Chagres | Plan of reduction in energy consumption | ✓ | ✓ | ✓ | - | ✓ |
| Collahuasi | Collahuasi | Energy and climate change management system | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | Platform—online measurement of variables | ✓ | - | ✓ | - | - |
| | | Use of NCRE | - | ✓ | - | ✓ | ✓ |
| | | Carbon footprint measure | - | - | - | ✓ | ✓ |
| Antofagasta Minerals | All operations | Energy and climate change management system | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | Use of NCRE | - | ✓ | - | ✓ | ✓ |
| | | Use of NCRE | - | ✓ | - | ✓ | ✓ |
| | Los Pelambres | Use of NCRE | - | ✓ | - | ✓ | ✓ |
| | | Innovation project | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | Optimisation of processes | ✓ | ✓ | ✓ | - | ✓ |
| | Centinela | Use of NCRE | - | ✓ | - | ✓ | ✓ |
| | | NCRE agreements | - | - | - | ✓ | ✓ |
| | | Optimisation of processes | ✓ | ✓ | ✓ | - | ✓ |
| | Zaldivar | Use of NCRE | - | ✓ | ✓ | ✓ | ✓ |
| | | NCRE agreements | - | - | - | ✓ | ✓ |
| | Antucoya | Optimisation of processes | ✓ | ✓ | - | ✓ | ✓ |
| BHP Chile | All operations | Climate change management system | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | Electric central to natural gas | - | - | - | - | ✓ |
| | Escondida | Energy efficiency plan | ✓ | ✓ | ✓ | - | - |
| | | Energy balance | ✓ | ✓ | ✓ | - | - |
| | | Optimisation of processes | ✓ | ✓ | ✓ | - | - |
| | | NCRE agreements | - | ✓ | - | ✓ | ✓ |
| | Spence | NCRE agreements | - | ✓ | - | ✓ | ✓ |
| | | Energy efficiency plan | ✓ | ✓ | ✓ | - | - |

Table 4. Cont.

| Organisation | Operation | Environmental Management Initiatives | Reduction in Energy Consumption | Energy Cost Reduction | Improve Energy Efficiency | Reduce Fossil Fuels Dependency | Climate Change |
|--------------|---------------------|---|---------------------------------|-----------------------|---------------------------|--------------------------------|----------------|
| CODELCO | All operations | Energy and climate change management system | ✓ | ✓ | ✓ | - | ✓ |
| | | NCRE agreements | - | - | - | ✓ | ✓ |
| | | Electric vehicles | - | ✓ | - | ✓ | ✓ |
| | Teniente | Innovation project | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | Hybrid LHD | - | ✓ | - | ✓ | ✓ |
| | | Use of NCRE | - | ✓ | - | ✓ | ✓ |
| | Chuquicamata | Optimisation of processes | ✓ | ✓ | ✓ | - | ✓ |
| | Andina | Optimisation of processes | ✓ | ✓ | ✓ | - | ✓ |
| | Gaby | Use of NCRE | ✓ | ✓ | - | ✓ | ✓ |
| | Salvador | Innovation project | - | ✓ | - | ✓ | ✓ |
| Teck Chile | All operations | Energy efficiency plan | ✓ | ✓ | ✓ | - | - |
| | Quebrada Blanca | Use of NCRE | - | ✓ | - | ✓ | ✓ |
| | Carmen de Andacollo | Optimisation of processes | ✓ | ✓ | ✓ | - | ✓ |
| | | Use of NCRE | - | ✓ | - | ✓ | ✓ |

In addition, Table 5 shows a resume regarding the energy consumption for each mining operation, energy efficiency, GHG emissions, GHG emissions intensity, the specific main Environmental Management Initiatives to face energy challenges detected, and their benefits.

Table 5. Total energy consumption and the main EMIs to deal with energy challenges for each mining operation and their associated benefits.

| Operation | Energy Consumption Miles GJ ^{2,3} | Energy Efficiency GJ/tCu ^{1,2} | GHG Emissions tCO ₂ e ² | GHG Emissions Intensity tCO ₂ e/tCu ^{1,2} | The Main EMIs to Face Energy Challenges Detected | Benefits Associated to EMIs |
|---------------------------------------|--|---|---|---|--|---|
| Anglo American, All global operations | 11,337.0 | 30.6 | 1,065,008.0 | 2.9 | NCRE agreement, 3 terawatt-hours per year. | CO ₂ emissions by around 70%. |
| Anglo American, El Soldado | - | - | - | - | Improvement in the energy efficiency of haul trucks by reducing RPM of the engine. | Reduce operational cost and improve energy efficiency. |
| Anglo American, Los Bronces | - | - | - | - | Energy Management System. | Reduction of 4.9% in its energy during 2017. In addition, it helps to reduce GHG by 4.0%. |
| | | | | | A prototype of start/stop for trucks. | A reduction in fuel consumption of 0.5% by 2016. |
| | | | | | Photovoltaic plant on a tailings dam. | By 2020 it generated 510 GJ and reduced 54 tCO ₂ e. |
| | | | | | Big Data—computational tools. | By 2017 a reduction of 3% in energy consumption. |

Table 5. Cont.

| Operation | Energy Consumption Miles GJ ^{2,3} | Energy Efficiency GJ/tCu ^{1,2} | GHG Emissions tCO ₂ e ² | GHG Emissions Intensity tCO ₂ e/tCu ^{1,2} | The Main EMIs to Face Energy Challenges Detected | Benefits Associated to EMIs |
|---|---|--|--|--|---|--|
| Anglo American, Chagres | - | - | | | Energy efficiency plan. | A reduction of 6.4% energy consumed and 4.4% in tCO ₂ e by 2017. |
| | | | | | Increased boiler efficiency by 10%. | Expected reduction of 700,000 kWh/year. |
| Collahuasi | 11,576.0 | 20.5 | 1,853,287.0 | 2.9 | NCRE agreement. | By 2025, 100% of the electrical energy will be from renewable energy. It would allow the company to reduce around 394 thousand tons of GHG from scope 2. |
| Antofagasta Minerals, all global operations | 24,121.0 | 31.3 | 2,345,212.0 | 3.2 | Use of NCRE. | Around 21% of the company's total energy comes from NCRE. |
| Antofagasta Minerals, Antucoya | 2143.0 | 29.8 | 272,664.0 | 3.4 | Reduction in fuel consumption in the mining haul trucks by a logistic strategy. | A reduction of 2161 m ³ of diesel a year, which is around 6461 tCO ₂ e/year. |
| | | | | | A reduction in the size of ore feed by optimizing its processes. | An energy saving of 2744 MWh and a reduction in emissions of 1088 tCO ₂ e per year. |
| Antofagasta Minerals, Centinela | 10,398.0 | 37.6 | 1,034,516.0 | 4.2 | Solar thermal—substitution of around 55% of the diesel consumed for solar energy. | Saving around USD 2,000,000 per year. |
| | | | | | NCRE agreement. | All its energy from renewable sources by 2022. |
| | | | | | Optimization of processes by Mine to Mill initiative. | A reduction of 58,148 MWh/year in electricity and 23,421 tCO ₂ e a year. |
| Antofagasta Minerals, Los Pelambres | 8120.0 | 22.3 | 722,293.0 | 2.0 | Solar energy—energy generation from a photovoltaic plant. | Solar and wind energy produce 59% of the total energy required—reduction in GHG of the mining production |
| | | | | | Wind energy—energy generation from a wind farm “El Arrayan”. | Solar and wind energy produce 59% of the total energy required—reduction in GHG of the mining production. |
| | | | | | Innovative system, energy generation by its conveyor belts. | Around 10% of the total energy requirement. |
| | | | | | VFD installed on one of the impulsion pumps. | This strategy represented a saving of 1548 MWh/year and a reduction of 587 tCO ₂ e/year in emissions. |

Table 5. Cont.

| Operation | Energy Consumption Miles GJ ^{2,3} | Energy Efficiency GJ/tCu ^{1,2} | GHG Emissions tCO ₂ e ² | GHG Emissions Intensity tCO ₂ e/tCu ^{1,2} | The Main EMIs to Face Energy Challenges Detected | Benefits Associated to EMIs |
|--------------------------------|---|--|--|--|---|---|
| Antofagasta Minerals, Zaldívar | 3460.0 | 29.8 | 315,028.0 | 3.3 | Optimization of processes with different actions such as a performance increment SAG or in the efficiency of the coarse ore transport system. | A reduction of 87,463 MWh/year in electricity, 37,764 tCO ₂ e/year and 674,409 L of diesel a year. |
| | | | | | Biomass—creation of centre called CEADA. | Reducing the GHG and generating adaptation for some species in arid zones. |
| | | | | | Renewable energy agreement with Colbun S.A (electricity generator and distributor). | From 2020, the operation uses only electricity from renewable sources. Reduction in scope 2 GHG emissions by 67,615 tCO ₂ e. |
| BHP, all global operations | 39,668.8 | 28.91 | 5,024,000.0 | 3.7 | Management system—to identify different risks and implement activities to reduce GHG Emission. | Reduce cost and GHG emissions—seeking new energy resources. |
| BHP, Escondida | 32,334.1 | 27.97 | 4,180,000.0 | 3.9 | The organization modified the project into a natural gas combined-cycle unit (Kelar). | By 2017, they Reduced around 203,344 tCO ₂ e per year. |
| | | | | | Hecker project cathode—alternating current for the copper deposition (electrowinning process). | A reduction of around 11 GWh a year. |
| | | | | | An agreement with an electricity supplier to ensure a 100% renewable power source. | A reduction in GHG, seeking zero GHG emissions from scope 2. This change would reduce around 3320 k tCO ₂ e. |
| | | | | | Change to the design and materials of ball mills. | Energy consumption reduction between 3 to 5%, which represents 30,000 MWh/year. |
| BHP, Cerro Colorado | 2976.0 | 43.19 | 244,000.0 | 3.7 | - | - |
| BHP, Spence | 4358.7 | 29.73 | 600,000.0 | 3.4 | Energy efficiency strategy to improve the EW process. | Savings of 5% per year in electrical energy in the EW process, which is around 7,431,026 kWh/year. |
| | | | | | Change in mining trucks to Komatsu 980E electric trucks. | Saving of 7% in fuel for trucks. |

Table 5. Cont.

| Operation | Energy Consumption Miles GJ ^{2,3} | Energy Efficiency GJ/tCu ^{1,2} | GHG Emissions tCO ₂ e ² | GHG Emissions Intensity tCO ₂ e/tCu ^{1,2} | The Main EMIs to Face Energy Challenges Detected | Benefits Associated to EMIs |
|--------------------------------|---|--|--|--|---|--|
| CODELCO, all global operations | 51,954 | 32.11 | 4,532,359 | 2.8 | An agreement with an electricity supplier to ensure a 100% renewable power source. | A reduction in GHG, seeking zero GHG emissions from scope 2. This change would reduce around 400 k tCO ₂ e. |
| | | | | | KPIs regarding energy efficiency and a corporate regulation about this topic for new projects. | Reduce cost and GHG emissions—seeking new energy resources and to foster energy efficiency. |
| | | | | | The organization modified some agreements of electric supply for the northern operations. | Around 22.5% of the total energy consumed will be from renewable energy sources. |
| CODELCO, Teniente | 9642 | 21.8 | 888,081.0 | 2.0 | Use of renewable energy—a runoff river mini-power plant which uses tailing as an energy source. | Plant produces 2.4 MW (around 20,000 MWh/year). |
| | | | | | Hybrid LHD. | A reduction in diesel consumption of over 25% and operational cost of 30%. |
| CODELCO, Chuquicamata | 12,988 | 32.4 | 1,155,199 | 2.9 | Solar energy—energy generation from a solar plant (Calama Solar 3). | Plants provide 1.1 MWp and a reduction of 1680 tons of CO ₂ a year. |
| | | | | | VOD—automatically distributes the air according to the instant demand in the mine. | Reduction of around 20% to 50% of the energy consumed. |
| | | | | | NCRE agreement for the electricity supply contract. | 80% of the supply comes from NCRE and it allows a reduction in GHG from scope 2. |
| CODELCO, Gaby | 3212 | 31.5 | 269,019 | 2.6 | Solar thermal—a solar thermal plant called Pampa Elvira Solar. | Reduction of around 15,000 tons of CO ₂ annually. |
| CODELCO, Andina | 4982 | 27.0 | 444,227 | 2.41 | VOD—automatically distributes the air according to the instant demand in the mine. | Reduction of around 25% of the energy consumed. |
| CODELCO, Salvador | 2688 | 47.7 | 300,059 | 5.33 | New technology through hydrogen as a catalyst in mining haul trucks' engines—hybrid use of diesel | A reduction of around 10 to 20% of the cost. |
| CODELCO, Radomiro Tomic | 9840 | 37.8 | 752,756 | 2.89 | - | - |

Table 5. Cont.

| Operation | Energy Consumption Miles GJ ^{2,3} | Energy Efficiency GJ/tCu ^{1,2} | GHG Emissions tCO ₂ e ² | GHG Emissions Intensity tCO ₂ e/tCu ^{1,2} | The Main EMIs to Face Energy Challenges Detected | Benefits Associated to EMIs |
|---------------------------|--|---|---|---|--|---|
| CODELCO, Vetanas | 3004 | - | 211,206 | - | - | - |
| CODELCO, Ministro Hales | 5597 | 32.8 | 511,812 | 3.00 | - | - |
| Teck, Quebrada Blanca | - | 49.7 ** | - | 5.99 ** | Solar energy—agreement with AES Gener to supply energy from renewable sources. | 30% of the total energy consumed for Quebrada Blanca—reduce GHG. |
| | | | | | NCRE agreement for the electricity supply contract. | For the new project QB2, 50% of total operational needs will come from renewable resources. A reduction of 800,000 tCO ₂ e per year. |
| Teck, Carmen de Andacollo | 2104 | 34.5 | 211,316 | 3.46 | Optimization in grinding and blasting process—identifies the different hardness in the rock. | Saving around 600,000 USD per year and 2060 tCO ₂ e. |
| | | | | | NCRE agreement for the electricity supply contract. | 100% of renewable energy for the operation. A reduction of 200,000 tCO ₂ e per year. |
| | | | | | Change in medium to fine liners in the lining of the 20 K Plant cone crushers. | A reduction of 4.1 TJ and 471 tCO ₂ e per year. |
| | | | | | The installation of a sizer-type crusher. | An energy reduction of 8.9 TJ and 1042 tCO ₂ e per year. |
| | | | | | Optimization of the lifter angle of the SAG mill. | A reduction of 12.2 TJ of energy and 1413 tCO ₂ e per year. |

¹ tCu corresponds to tons of fine copper. ² The data of energy consumption, energy efficiency, GHG emissions and GHG intensity are from 2020. The exception is Teck, Quebrada Blanca ** for which the data used are from 2018 because there were no available data after that year. ³ The energy consumption considers electricity and fuel consumption.

5. Discussion

5.1. Initiatives for Water Challenges and Their Benefits

In this article, the most relevant literature regarding water and energy challenges for copper mining in Chile was reviewed. The research method applied allowed obtaining an adequate description of the mining industry area, after carefully investigating the selected documents to answer the research questions. Through the review process, it is possible to synthesize the various sustainability strategies presented by mining companies and study their diverse benefits. After studying several companies, it is possible to appreciate that they have acknowledged most of the challenges discussed as a significant concern, disclosing them in their reports, institutional politics, web pages, news, and projects, among others. In the case of water challenges, the companies reviewed focus most of the EMIs on coping with hydric scarcity because it is a critical issue in the mining companies' regions. They are more aware of the need to find solutions to address this issue [22]. There is evidence that hydric scarcity is a critical issue.

For instance, because of the drought in May 2020, Teniente had reduced copper processing [114]. Hydric scarcity affected the mining industry and agricultural sector in Chile [8]. Water supply must be reduced for the mining industry to cope with agricultural

demand. This situation is described as ‘water grabbing’, in which there is direct competition between different water users [115].

Water pollution is another matter that is highly relevant for companies because they have developed various plans to ensure compliance with national regulations and reduce negative social impacts and prejudicial effects on water sources [69]. Water pollution from the mining industry is not a recent issue [45]. Examples from China, Finland, Papua New Guinea, Australia, and Canada showed that failure in managing effluents has resulted in groundwater contamination.

Figure 3 presents a scheme whereby it is possible to identify that seawater use and community strategy plans address most of the challenges to understanding the relationship between water challenges and dominant initiatives. Three of the identified challenges might be dealt with by the management systems and monitoring programs, while two by water recirculation systems.

EMIs related to water challenges allow the organisation to reduce the hydric stress, ensuring enough water supply for the operation. They can increase resilience in facing an unexpected event. An example is the case of Los Bronces in 2014, whereby it had lost productivity because of extreme drought. However, the company have improved its water recirculation system, reducing freshwater consumption and dependency [76].

Seawater use is one of the most dominant activities, with projections showing that this resource will increase by approximately 289.9% by 2028, with the concentrations process using the most amount [22]. The desalination strategy has also been used globally. As of June 2015, there were 18,426 desalination plants, providing more than 86.8 million m³ per day worldwide [116]. For the Chilean companies, using seawater is more costly compared to traditional water sources, i.e., around USD 3.5/m³ more. However, since water is scarce in the north of Chile, most of the companies rely on some alternative sources. They relate most of the costs to electricity consumption, which contradicts reducing energy consumption [9,117].

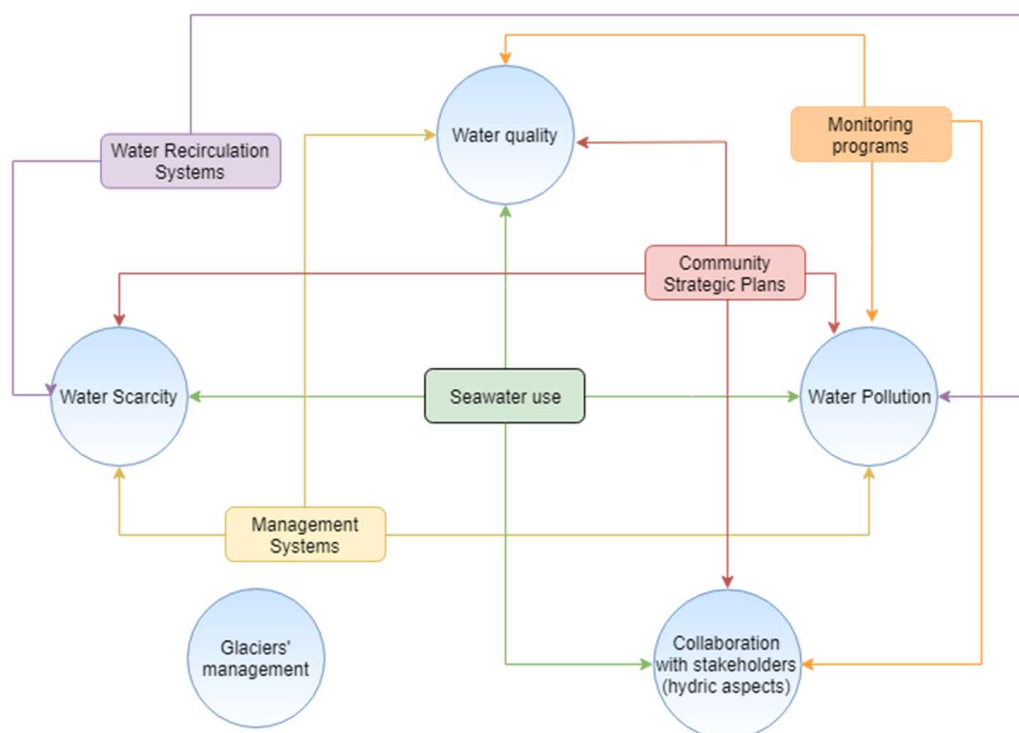


Figure 3. The relationship between water challenges and dominant initiatives used by copper mining companies in Chile.

Some alternatives to reduce operational costs are necessary to achieve a more cost-effective desalination process [32]. However, it needs more effort to reduce energy costs, and a shared supply network between different companies might be an alternative for reducing the energy prices [9,117]. The high operating costs of desalination may result in low water production, such as in Spain [118]. Some desalination companies were only operating at 10% capacity due to high costs. Another option is to adapt processes to use seawater without desalination, as in Antucoya or Sierra Gorda.

Community Strategic Plans are another initiative that companies have used, in which the dominant strategy is cooperatively improving the drinking water system [53]. Improved drinking water access is also one of the new Sustainable Development Goals (SDGs), and it is essential to be realised [119]. This action can help reduce the hydric stress condition in the influence area, improve the relationship between stakeholders, and enhance the SLO [25,120]. With management systems, most of the base is on the ICMF Framework and risk system, which might support companies in setting concrete plans and goals. With audits, it is possible to generate ongoing reports and evaluate the fulfilment of the commitments made. Some organisations use water balance in management systems to determine water consumption for different stages, identifying potential issues [121].

Monitoring programs are another dominant EMI, which allows organisations to test water quality in different extraction points. One strategy is working with communities. One example is Pelambres's plan, which developed representative participation of diverse stakeholders, resulting in an online website that enhances the transparency and legitimacy of the monitored information [82]. Ghana's government has undertaken the same initiative to manage the country's groundwater resources. More field monitoring activities are taken to control pollution, illegal mining operations, and water body encroachment while monitoring the water quality [122]. A new method to assess the water life cycle, called the water footprinting method, has been developed by the Water Footprint Network. This method has been used to identify the potential environmental impacts of water in the mining industry [45].

Water recirculation is an important initiative for the mining industry to face hydric scarcity, with a global recirculation of around 70% [46]. There are different methods in which the most common sulphide minerals are thickeners and pumps to reuse water from tailing dams into the process [22]. In the strategies studied, it is possible to highlight the use of Thickened Tailings technology, which allows tailings to have a substantial percentage of around 67–70%, maximising water recuperation. This technology can provide other significant benefits, such as stabilising the tailing dam and reducing its evaporation [80]. However, water recirculation is complex and has its disadvantages [28]. Long-term recirculation increases the chemical concentration in flotation and the accumulation of microorganisms, which may harm the environment and social aspects of a leak in the water recirculation plant.

Despite the companies' efforts to acknowledge the challenges, there are some challenges that they have considered minor compared to others in their EMIs. For example, glaciers' management is the least considered, where CODELCO Andina and Antofagasta Minerals include glaciers into their operational planning, even though glaciers are critical water sources, and adverse effects on these ice masses can reduce water availability [66]. Currently, there is a discussion about the Glacier Protection and Preservation Law (GPPL) in Chile, which seeks to enhance the glaciers' preservation status because of their relevance in water supply, biodiversity, and tourism. The first draft of the GPPL was in 2006. However, there is currently no approved law due to a lack of agreement in some specific landform classifications and issues with conflict of interest [123]. In this context, a study regarding the proposed GPPL showed that if this law project is approved, copper production will reduce by around 22.5%, affecting the operations of some crucial companies such as Andina, Teniente, Los Pelambres, and Los Bronces [124].

5.2. Initiatives for Energy Challenges and Their Benefits

The most common strategies for the companies studied are the use of NCRE, Optimisation of processes, Management Systems, Energy Efficient Plans and Innovation projects, where Figure 4 shows the relationship between initiatives and energy challenges.

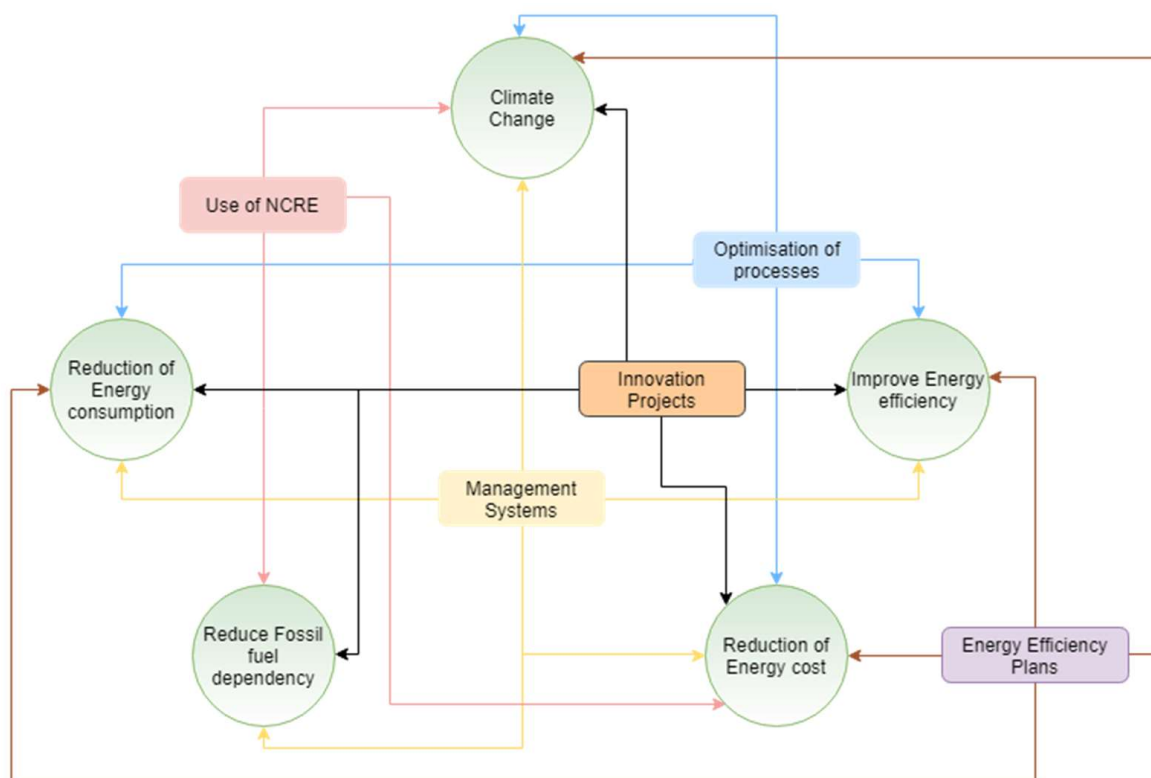


Figure 4. The relationship between energy challenges and dominant initiatives used by mining companies in Chile.

The initiatives address most of the energy challenges. Management systems can provide a guideline to generate goals and common standards for the organisations, where most companies reviewed focus on climate change and energy efficiency. It is essential to highlight that some companies such as Teck have an Environmental Management System that covers water and energy challenges. Conversely, some companies have these topics separate, such as Anglo American. However, both strategies have integrated water and energy aspects into the decision-making process.

Innovation is a relevant aspect of the mining industry because it can generate competitive advantages and better use of current resources. There are several innovations into the initiatives reviewed, such as the conveyor belt capable of generating around 10% of total energy in Los Pelambres, the trucks tested with hydrogen in El Salvador, the electric vehicle used in CODELCO, and the hybrid LHD in Teniente, among others. The innovation is not only limited to the use of new machinery but also includes remote operation [125]. One example is Remote Operations Centres (ROC) in the mining operation to control mines, ports, and railways. In this sense, all innovative projects need the collaboration of different actors, with research playing an essential role in finding innovative solutions for energy challenges [31].

In the case of the optimisation process and the energy efficiency plan, it is possible to identify their connection because some energy efficiency programs can generate guidelines for seeking opportunities to reduce energy consumption [73]. Although both strategies might deal with four energy challenges, it is less common that these actions could reduce fossil fuel dependency. One reason might be that the strategies focus on modifying current processes to reduce energy consumption rather than generating changes in energy sources. Within the optimisation strategies studied, it is possible to highlight the VOD developed in Andina and Chuquicamata, where this strategy reduces 20 to 30% of the energy consumed by the ventilation process through automation of air distribution based on demand [110].

The most common NCRE strategy is solar energy, reducing the dependency on fossil fuels and GHG emissions. Besides Chile, other mining countries have executed solar projects in their mining industries, such as Ghana, Australia, Eritrea, the United States, and Canada [126]. However, renewable energies do not mean an energy consumption reduction or improvement in the energy efficiency indicator (energy consumed per ton of mineral produced), as renewable energies replace conventional sources [72].

Companies need to foster both energy efficiency strategies and the use of renewable sources to achieve sustainable production [31]. There are two types of strategies that are possible to identify within the initiatives. First, some companies have created alliances to install their solar thermal plant, such as Gaby [49]. Secondly, there are also other companies that have signed the agreements with energy suppliers to ensure that energy comes from renewable sources. For instance, Zaldivar is trying to become the first company to produce copper solely with renewable energy by 2020 or QB2, attempting to ensure the use of NCRE at the beginning of its operation [96]. Different companies such as Collahuasi, Centinela, Escondida, Spence, Chuquicamata, and Carmen de Andacollo seek to reduce their GHG emissions from scope 2 by agreement, which ensures to supply energy from renewable sources.

The advantages of using renewable energy can be multiple, such as improving the corporate reputation, obtaining the SLO, and reducing GHG emissions [14]. Renewable energy sources also can reduce operational costs in the long term. For instance, Centinela saves around USD 2,000,000 in diesel per year by implementing the solar thermal plant [82]. From the environmental aspect, the utilisation of renewable energy may improve polluted mine sites [127].

However, the reduction in fossil fuel dependency is the least discussed issue compared to the decrease in energy costs, which is the most addressed in strategies where companies seek to increase the efficiency of copper production [14]. Some initiatives aim to decrease fossil fuel dependencies, such as NCRE agreements with energy suppliers, process optimisation, and electromobility. These initiatives may face climate change issues, a topic frequently discussed by companies because they are currently seeking to reduce their GHG emissions [72]. However, although renewable energy helps reduce fossil fuel consumption, avoiding them is a difficult challenge for companies, especially when thermoelectric is the primary energy production source in the national electric system [72].

6. Conclusions

The demand for water and energy consumption, which are critical supplies for productivity in the copper mining industry, is increasing. Based on this research, the main water and energy challenge is water scarcity in the mining companies' regions, which answered the first research question. In this review, companies might be aware that water availability is insufficient to meet current demand as most EMIs try to address this issue. Chile's mining industry has demonstrated that it is working to deal with the current water challenges.

Glacier management is less discussed as most sustainability reports do not consider this matter. Even though not all companies directly impact glaciers, there are clear events such as the "Pascua-lama" project. The company lost the money invested due to inadequate management and its social reputation. There is evidence that companies should consider

glaciers in their plans to avoid issues with stakeholders, future projects, and environmental impacts, especially with the government's discussion of glacier law, which can be an issue for some companies and jeopardise their operations.

Since the EMIs address most energy challenges, the companies studied recognise them as relevant to their planning process. Energy cost reduction is the topic that companies have tried to cope with the most, and it is associated with more strategies. However, energy efficiency is a significant challenge because companies seek to reduce operational costs and become more cost-effective. This study revealed more than one dominant strategy reflecting sustainability as a crucial concern for the mining industry. The most predominant management systems have served as a guideline for companies, helping them standardise processes, define clear goals, and track them.

Meanwhile, in response to the second research question, the result showed that using seawater and renewable energy are the dominant initiatives implemented by companies. The utilisation of these initiatives provides opportunities for the mining industry to expand into new projects. However, renewable energy and seawater necessitate the implementation of an energy efficiency plan to avoid increasing production costs. The copper mining companies must promote energy efficiency strategies and alternative sources to reach sustainable and cost-effective production, with innovation as a catalyst.

Finally, the third research question was addressed. Implementing EMIs can provide multiple benefits, including enhanced SLO, increased supply availability, reduced GHG emissions, and lower operational costs. These enable mining companies to become more sustainable over time and more resilient to unexpected events. Copper industry companies should analyse their objectives as one big goal to reduce the conflict between the strategies used. It happens, for instance, with the desalination process, which can help reduce water stress due to water scarcity. However, the amount of energy consumed increases, resulting in an increment in operational costs and less efficient production. Furthermore, companies must apply current knowledge about developed strategies to address energy and water issues. The experience can be helpful to generate future projects to ensure sustainable production, considering environmental, economic, and social aspects.

Finally, this research has some limitations to consider. One is the availability of information. Although the analysis was conducted using information presented by the companies and official government reports, specific strategies were not included in its strategic plan. Another significant constraint is the mining companies' operating conditions in Chile. Although this research reviewed several sustainability strategies for different mining operations, the studied challenges have a local character. Thus, the relationship between EMIs and the identified challenges is dependent on the similar conditions that mining companies and countries have.

Author Contributions: Conceptualization, J.L.G.; methodology, J.L.G.; validation, I.O.; formal analysis, J.L.G. and I.O.; investigation, J.L.G.; writing—review and editing, J.L.G.; supervision, I.O. All authors have read and agreed to the published version of the manuscript.

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Appendix A. Diagram for the Research Process

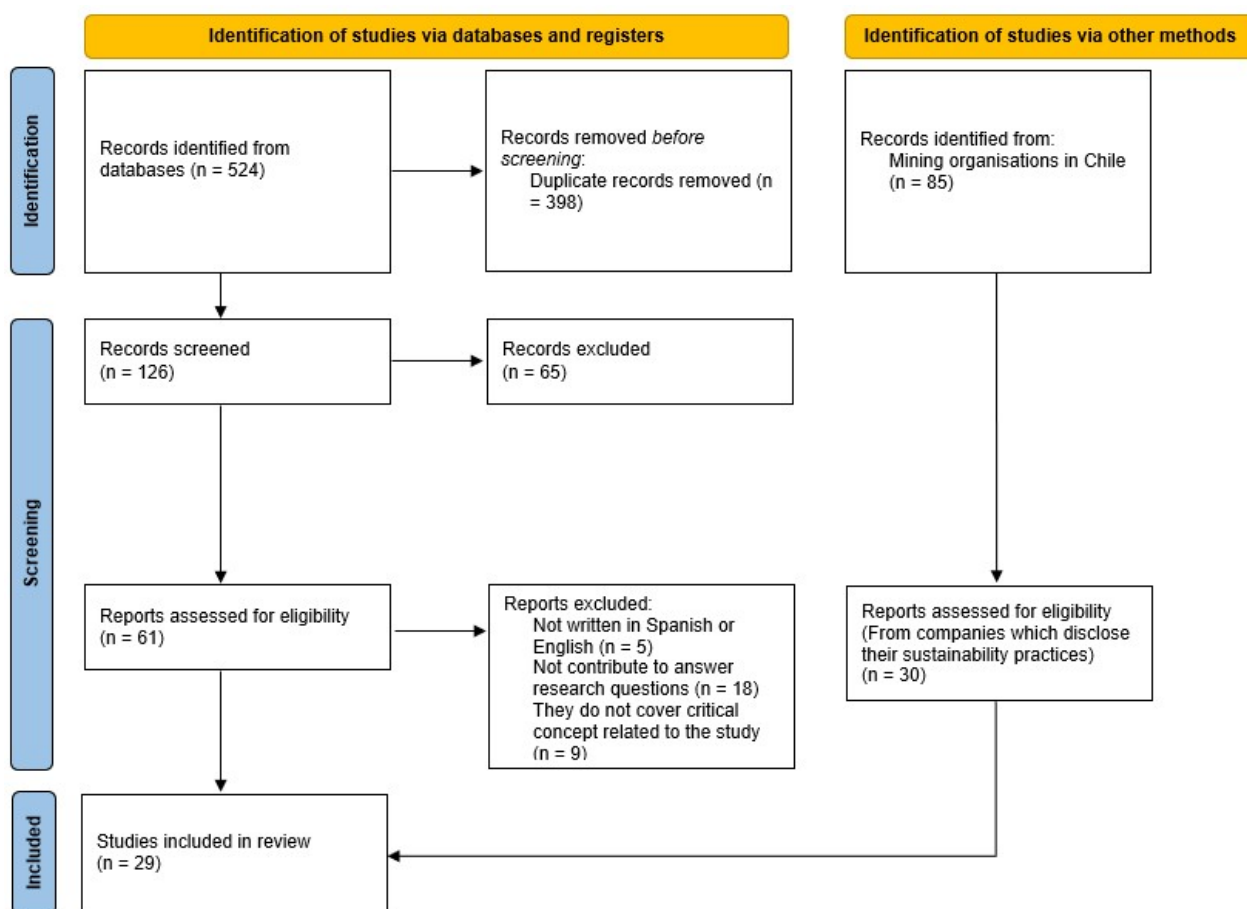


Figure A1. A flow chart adapted from the PRISMA 2020 statement which presents the literature included [128].

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