Copper mining in Chile and its electric power demand

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Summary

This thesis contains research into the copper mining industry in Chile. It investigates into the processes and methods of copper extraction, both pyrometallurgical and hydrometallurgical. It also covers the desalination industry for copper mining and its electric power consumption.

One of the results is a summary of the electric and thermal power consumption of copper mines in Chile based on mine type, type of process, and annual production rate. The copper mines are also illustrated on a map to indicate geographical location. Based on the results of electric and thermal power consumption of copper mines, as well as the ongoing trends in the copper mining industry in Chile, this thesis gives suggestions on how Wärtsilä Power Plants solutions would be a viable option for electricity supply to mine owners in Chile.

The methodology of this thesis has been to study previous academic research alongside governmental and local reports from Chile. In addition to primary research an interview has also been conducted.

Language: English Key words: copper mining, SX-EW, copper concentrate, desalination, Chile, power, Wärtsilä

EXAMENSARBETE

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Abstrakt

Det här examensarbetet innehåller forskning om koppargruvindustrin i Chile samt processer och metoder för pyromteallurgisk och hydrometallurgisk kopparutvinning. Arbetet täcker också industrin om avsaltning av havsvatten för koppargruvindustrin, vilket är en ökande trend i Chile.

Ett av resultaten är en sammanfattning av el- och värmebehoven för koppargruvor i Chile baserat på gruvan, typ av process, och den årliga produktionsnivån. Dessa gruvor är också utplacerade på en karta för att illustruera deras geografiska läge. Baserat på de här resultaten, samt de pågående trenderna inom koppasgruvindustrin i Chile, ger arbetet förslag på hur Wärtsilä Power Plants lösningar skulle vara ett bra alternativ för elfsörsrjning till gruvägare i Chile.

Metodiken för examensarbetet har varit att studera tidigare akademisk forskning samt statliga och lokala rapporter från Chile. Förutom litteraturstudier har också en intervju blivit gjorts för att få djupare insikt.

Språk: Engelska Nyckelord: copper mining, SX-EW, copper concentrate, desalination, Chile, power, Wärtsilä

OPINNÄYTETYÖ

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Tiivistelmä

Tämä opinnäytetyö sisältää tutkimuksen kuparin kaivosteollisuudesta Chilessä. Se tutkii pyro - ja hydrometallurgisia kuparin erottamismenetelmiä ja- prosesseja. Opinnäytetyö kattaa myös suolanpoistomenetelmät merivedestä kuparikaivos teollisuudessa, ja sen sähkönkulutuksen.

Yksi tuloksista on yhteenveto sähkö- ja lämpöenergian virrankulutuksesta kuparikaivoksilla Chilessä perustuen kaivokseen, prosessityyppiin ja vuotuiseen tuotantotasoon. Nämä kaivokset on myös sijoitettu kartalle kuvamaan niiden maantieteellistä asemaa. Näihin tuloksien pohjautuen sekä nykyisiin trendeihin Chilen kupariteollisuudessa opinnäytetyö antaa ehdotuksia siihen miten Wärtsilä Power Plantsin ratkaisut voisivat olla hyvä ratkaisu sähköhuoltoon Chilen kaivosten omistajille.

Tutkimusmetodina opinnäytetyössä on käytetty sekä aikaisempien akateemisten tutkimusten että Chilen valtiollisten ja paikallisten raporttien tutkimista. Kirjallisuuden tutkimuksen lisäksi on tehty myös haastattelu saadakseni parempi käsitys aiheesta.

Kieli: Englanti Avainsanat: copper mining, SX-EW, copper concentrate, desalination, Chile, power, Wärtsilä

Contents

1 Introduction

I have studied mechanical and production engineering at Novia University of Applied Sciences since 2010. Since the summer of 2012 I have been a summer trainee at Wärtsilä Power Plant for the sales department Americas region. In 2014 they asked me if I was interested in writing my bachelor's thesis for them. The thesis would be in the area of mining industry in the Americas region, which links to the work I have completed throughout the last three summers.

1.1 Wärtsilä Power Plants

Wärtsilä is a global leader of complete lifecycle power solutions for the marine and energy markets. The company has three subdivisions: Ship Power, Power Plants and Services. The employer for this thesis is Wärtsilä Power Plants, a leading global supplier of power plants for the decentralised power generation market. Wärtsilä's portfolio includes unique solutions for baseload, peaking and self-generations as well as for the oil and gas industry. The strengths of Wärtsilä power plants are their flexible design, high efficiency and low emission levels. (Wartsila.com, 2015)

In 2014, Wärtsilä Power Plants' net sales totalled EUR 1,138 million with approximately 980 employees. The total installed power plant capacity was 55 GW in 169 countries around the world. (Wartsila.com, 2015)

1.2 Background

Wärtsilä was aware that the mining industry South America South, which is an internal sales region in the sales department, is very electricity-intensive, and thus has great potential for business and for capturing a share of the power generation market. Naturally, this thesis was not able to research into all mining industries in South America South – which consists of Argentina, Bolivia, Chile and Peru. Therefore I will start the initial research process of this thesis by identifying the mining industry with the largest potential in this region, which is copper, gold and silver in Chile and Peru. Once I have discovered this, I will then focus my research specifically onto the copper mining industry in Chile, which is the largest mining industry in South America and one of the largest in the world.

1.3 Purpose

The main purpose of this thesis is to investigate the copper mining industry in Chile and explain the copper extraction processes and present their electricity and thermal power needs. From this information I will suggest how Wärtsilä's power plant solutions could be a viable opportunity for the copper mine owners in Chile.

In order to reach these goals I will study academic research alongside governmental and local reports from Chile. This data will give me a deeper insight into the current copper mining industry and the processes in use. In addition to primary research I will also conduct interviews with people involved in the copper mining industry in Chile.

1.4 Delimitation

The focus point of this thesis is on the copper mining industry in Chile. Copper mining is also a large industry in the neighbouring country Peru, which is one of Chile's biggest competitors, but unfortunately copper mining in Peru will not be investigated in this thesis due to the complexity of the investigation. It is important to state here that gold and silver mining is also a big industry in Chile and it is often a by-product of copper mining. They share many extraction processes and with copper mining are similar in many ways but will not be investigated within this thesis.

When looking at the energy consumption of copper mining there are two main categories and it is important to distinguish them: fuels and electricity. Both have a large share of the total cost of operation but they are not the same. Fuels and hydrocarbons, such as diesel, are used vastly for haulage and transportation, whereas electricity is used for other purposes such as grinding. These two energy sources are different and in this thesis electricity will be under the focus lens.

1.5 Disposition

- Chapter 2 describes the methodology.
- Chapter 3 will begin with outlining the different copper extraction methods and processes.
- Chapter 4 explains what the copper mining industry looks like in Chile today and in the future.
- Chapter 5 presents the electricity situation and consumption of copper mining industry in Chile.
- Chapter 6 explains copper mining processes' thermal demand.
- Chapter 7 introduces the new trend of desalination in the copper mining industry in Chile.
- Chapter 8 presents the results.
- Chapter 9 consists of summary and discussion of the results and further research.
- Chapter 10 ends with a conclusion and a personal evaluation.

1.6 Definitions and abbreviations

CHP – Combined heat and power.

Cochilco – Chilean Copper Commission, advises the Chilean government on matters concerning the production of copper and copper by-products.

Codelco – State-controlled miner and considered to be the world's largest producer of copper.

Communition – The process of reducing the size of the ore. Entails blasting, crushing and grinding.

Copper concentrates – A product of grinding and froth flotation consisting of roughly 30% copper. It can be processed metallurgically in a smelter. 45% of Chile's copper export is copper concentrates.

Desalination – A process that removes salts and other minerals from saline water. Use of desalinated water is a growing trend in the copper mining industry in northern Chile.

Electrorefining – An electrolytic refining process where copper anodes are dissolved and plated to produce high-purity copper cathodes.

Electrowinning – An electrolytic refining process where copper-loaded electrolyte produced by solvent extraction flows through a cell with inert anodes and metal cathodes. By applying a DC current the copper in the electrolyte plates onto the cathode producing high purity copper.

Fine copper – A measure of purity, 99.99% pure copper.

Froth flotation – is a process for separating hydrophobic materials from hydrophilic. This process is used for producing copper concentrates.

Hydrometallurgy – A branch of extractive metallurgy. Involves using aqueous chemistry for the recovery of metals. Common in Northern Chile.

kmt = kilo metric ton.

ktpd = kilo metric ton per day

kWh, MWh, GWh – kilowatt-, megawatt-, and gigawatt-hour. One watt is equal to 1 J/s.

Leaching – A widely used extractive metallurgy process which involves dissolving Cu^{2+}/Cu^{+} from copper ores into a H_2SO_4-H_2O solution, known as the lixiviant, to produce a pregnant leach solution (PLS).

LXSXEW – Refers to leaching, solvent extraction and electrowinning.

MJ/TMF – Megajoule per metric ton fine copper.

NCRE – Non Conventional Renewable Energy.

Open-pit – Most common type of mine today. Open-pit mining is accomplished by creating benches and terraces to gradually reach deeper under the earth's surface.

Pyrometallurgy – A branch of extractive metallurgy. Consists of smelting and purifying concentrates. The conventional way of producing fine copper.

SIC – Sistema Interconectado Central. Electric grid that covers the central region of Chile, including Santiago.

SING – Sistema Interconectado del Norte Grande. Electric grid that covers the northern region of Chile.

SX-EW – Solvent Extraction – Electrowinning. A hydrometallurgical extraction process that produces cathodes. Common in northern regions of Chile.

Ton – Metric ton, equals 1000 kg.

Underground mine – When open-pit mining is not feasible, miners dig a shaft and create tunnels to the ore deposits and follow the vein of the ore body and an underground mine develops.

tCu = Metric ton fine copper

2 Methodology

In this chapter I will explain the methodology of how the aims and goals of the thesis have been reached.

In order to reach these goals I have studied academic research, such as books and articles in relation to copper mining processes and copper mining industry in Chile. In addition to this I have also read governmental and local reports from Chile. This data has given me a deeper insight into the current copper mining industry and the processes in use.

To get a better understanding of the industry and get more detailed information that was not acquired through primary research, I have conducted an interview. This will give a more personal understanding in comparison to the more academic and statistical work that I have read.

3 Introduction to copper mining

In this chapter I will explain the processes of copper mining and production. There are two major methods of producing copper from copper ores. The first and conventional method is the pyrometallurgical route where copper ore is crushed, ground and concentrated to roughly 30%. The copper concentrate is then smelted, converted, fire refined and casted into copper anodes to reach 99.5% purity. Finally, to reach 99.99% purity the copper anodes are electrorefined to produce copper cathode, which is sold to the market.

The second method is hydrometallurgical and called SX-EW, which entails leaching, solvent extraction (SX) and electrowinning (EW) to create copper cathodes.

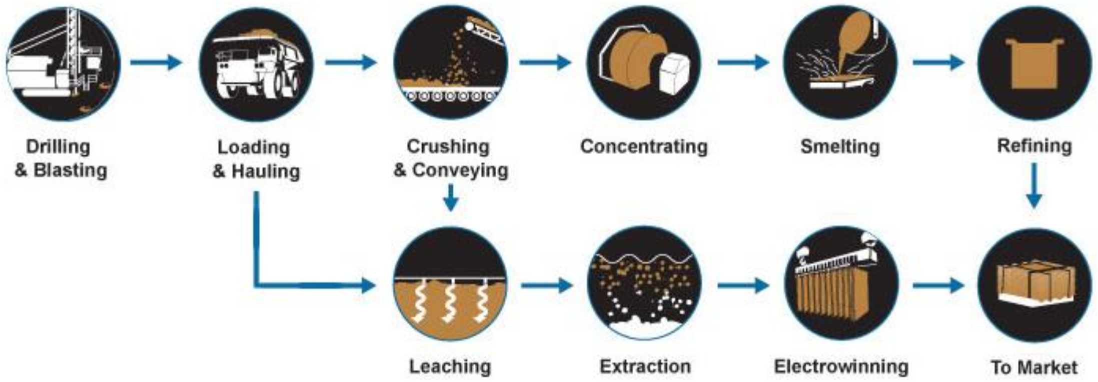


Figure 1. Flow sheet of copper mining processes for the conventional pyrometallurgical route and the hydrometallurgical method SX-EW. (Fcx.com, 2015)

3.1 Copper ore

In the earth's crust occurs about 250 copper minerals, however only a few of these are commercially important. The copper mineral is a result of reactions between hydrothermal solutions and the host rock influenced by chemistry, temperature, and pressure. Ores exposed to air are generally oxides and ores in oxygen-poor environments are sulfides. (Extraction and beneficiation of ores and minerals, 1994)

Most commonly encountered copper minerals:

Sulfide minerals

- Chalcopyrite ($CuFeS_2$)
- Covellite (CuS)
- Chalcocite (Cu_2S)
- Bornite (Cu_5FeS_4)

Oxide minerals

- Chrysocolla ($CuSiO_3$)
- Malachite (Cu_2CO_3)
- Azurite ($Cu_3(CO_3)_2(OH)_2$
- Cuprite (Cu_2O)

(Extraction and beneficiation of ores and minerals, 1994)

Two thirds of the copper extracted today come from porphyry copper deposits, which are the most important type of copper deposit. Porphyry copper deposits are found in the western North and South America and are therefore the type of copper deposit found in Chile. The most common mineral found in the porphyry copper deposits is chalcopyrite. The porphyry rock also contains other valuable metals such as gold, silver and molybdenum. The second largest type of copper deposit is sedimentary rocks which are found in Africa and Eastern Europe. (Doebrich, 2009)

According to Rosenqvist (2004), traditionally an ore is described as a rock which can be mined economically to serve as raw material for the production of metals. He points out that the economic aspect is very important, as it distinguishes what is an ore and what is worthless rock or gravel. The factors that decide whether it is an ore or worthless rock is the state of the technology and the market price of the metal. A century ago the copper ore had to contain 5% in order for it to be mined economically. Today the average copper ore in Chile is 0.85% but also lower grades down to 0.4% are economically feasible with certain extraction processes.

3.2 Copper mine types

There are two types of copper mines – open-pit and underground mines. Factors that determine what type of mine will be utilized are the ore body's Cu grade, shape, depth, reserves and location. The ore grade in underground mines usually has to be higher than in open-pit mines to make extraction economically feasible. This is due to the increased complexity of underground operations, such as tunnelling, ventilation, electric systems, water control and difficult logistics. (Extraction and beneficiation of ores and minerals, 1994)

Open-pit mining is the most common type of mine today due to its high production rates, safety, low costs and flexibility in operation. Open-pit mining is accomplished by creating benches and terraces to gradually reach deeper under the earth's surface. When the ore body cannot be reached economically by open-pit mining, miners dig a shaft to the ore deposit and from there follow the vein of the ore body and the underground mine develops. (Copper.org, 2015)

Figure 2. Escondida open-pit mine located in Northern Chile. (BHP Billiton, 2015)

3.3 Production of copper concentrates

Due to the low ore grade that is mined today in 2015 (0.5% - 2%), direct smelting is not economically feasible. It would require too much energy and furnace capacity to heat up and melt such a large quantity of rock that is of no value. For this reason, all ores destined for pyrometallurgical processing have to be concentrated before smelting. The most cost effective way of concentrating the copper ore is by froth flotation. Copper ores that undergo this process are the copper sulfide ores such as Chalcocite (Cu_2S), Chalcopyrite ($CuFeS_2$) and Covellite (CuS). (Copper.org, 2015)

The product of this process is copper concentrate, which contains 27-36% Cu, and the process entails:

- Reducing the size of the ore and liberating the Cu mineral grains from the non-Cu minerals, known as communition.

- Physically separating the liberated Cu-minerals from non-Cu minerals by froth flotation. The products are copper concentrate and tailings. (Copper.org, 2015)

3.3.1 Communition

The first step of concentrating copper is by reducing the size of the ore and liberating Cu-minerals from the copper ore so that they can undergo froth flotation, which is the next process. The process of reducing the size of the copper ore is called communition and is achieved in three stages:

a. Breaking the ore in the mine, open-pit or underground, with explosives. This is called blasting.

b. Crushing the blasted fragments by gyratory or jaw crushers.

c. Grinding the crushed ore in mills in several stages until desired size and Cu-mineral are liberated from the ore. (Schlesinger, 2011)

3.3.1.1 Blasting

The first stage of communition is blasting which involves drilling holes in a mine bench, filling them with explosives and igniting them electronically. The shock of the explosion cracks the rock into multiple fragments of roughly 0.1 m diameter. Smaller ore fragments are achieved by drilling holes closer to each other and the use of larger explosives. Optimizing blasting is important to achieve the smallest fragments possible to reduce the electric power needed to crush and mill the ore, which is very energy consuming. However, explosives are very expensive compared to electric power in respect to $/MJ. (Schlesinger, 2011)

3.3.1.2 Crushing

The second stage of communition is crushing of the ore and reducing its size step by step. The first or primary crushing is commonly performed with gyratory or jaw crushers since these units can handle larger rocks. This stage crushes the ore down to a size of 100 mm. The secondary crushing is performed by cone or roll crushers in order to reduce the size to less than 10 – 20 mm. The tertiary crushing is done by hammer mills and reduces the size down to under 5 mm. It should be noted that some concentration plants may only use primary crushing. (Schlesinger, 2011)

The first stage of primary crushing is usually done near the pit of open-pit mines or below the surface in underground mines, whereas the secondary crushers are usually located nearer the grinding mills. (Extraction and beneficiation of ores and minerals, 1994)

3.3.1.3 Grinding

The third and last stage of communition is grinding of the crushed ore in rotating mills where the Cu mineral grains are liberated from their non-Cu-mineral grains to a point where each mineral grain is free. (Schlesinger, 2011)

Concentrator plants often use a combination of rod and ball mills to grind the sulfide ores. (Extraction and beneficiation of ores and minerals, 1994)

The fine grinding can be done on dry minerals but is usually carried out with water creating a thick pulp. The ore-water mixture varies but is usually around 60-80% ore and 20-40% water. The grain size generally requires grinding to 50 - 100 µm diameters. An important step in the grinding process is ensuring right grain size for efficient flotation. This is generally carried out by hydroclones. (Schlesinger, 2011)

3.3.2 Froth flotation

After the sulfide copper ores have been blasted, crushed and ground in the communition process the wet slurry must undergo froth flotation to increase the concentration up to roughly 30 % in order to be economically transported and smelted.

The principles of froth flotation according to Schlesinger, 2011:

a. Reagents, known as collectors, are added to the slurry so the Cu minerals selectively become water-repellent (hydrophobic).

b. A stream of small rising air bubbles are blown from the bottom of the flotation cell that collides with the now water-repellent Cu minerals, resulting in Cu minerals getting attached to the rising air bubbles and floating up to the surface where a froth is created.

c. The still wetted non-Cu minerals do not attach to the rising air bubbles and remain in the slurry in the bottom of the flotation cell.

The froth overflows the flotation cell and is collected in a tank where the froth collapses. After flotation the froth is reground and cleaned which raises the total Cu concentration to roughly 30 %. The non-copper minerals that do not attach to the rising air bubbles will remain in the slurry, called the tailings. The flotation tailings, which account for about 98% of the concentrator’s ore feed, are stored in a dam close to the concentrator plan. The tailings usually contain 0.02 – 0.15 % Cu and the water in the tailings is recycled to minimize water consumption. (Schlesinger, 2011)

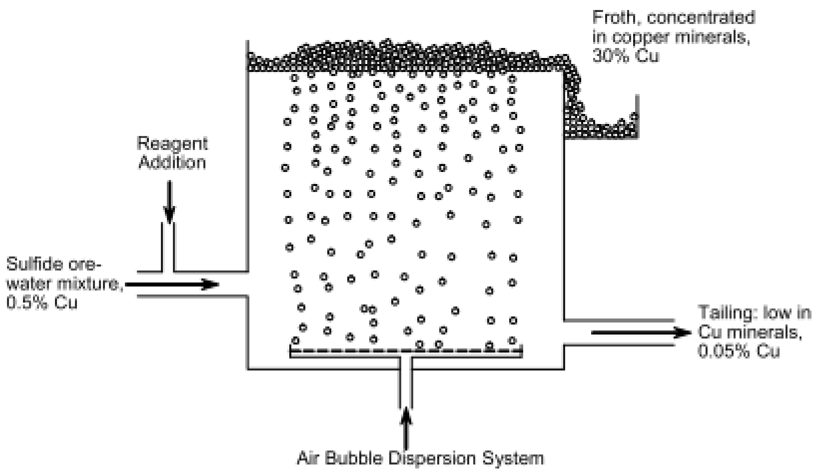


Figure 3. Reagents cause the Cu-minerals in the ore to attach to the rising air bubbles. The froth is collected and de-watered to become copper concentrate. (Schlesinger, 2011)

3.4 Pyrometallurgy

After the sulfide ores have been mined, crushed, ground and concentrated the copper concentrate must go through the conventional pyrometallurgical route in order to produce copper metal that can be sold to the market. Pyrometallurgy of copper can be structured into three main processes:

- Matte smelting
- Converting
- Fire refining and anode casting

The next stage after anode casting is electrorefining where copper cathodes are produced.

3.4.1 Matte smelting

Matte smelting is the most common way of smelting Cu-Fe-S concentrates. It involves heating, oxidizing, and fluxing the concentrates at high temperatures, 1250C. The primary objective of matte smelting is to oxidize the sulfur (S) and the iron (Fe) from the Cu-Fe-S concentrate. The three products of this process are (Schlesinger, 2011):

- Molten Cu-Fe-S matte that contains 45-75% Cu.

- Molten Fe silicate slag. Cu concentration in the slag can be from less than 1 % up to 7 %. For this reason smelter facilities have recovery processes of the slag.
- SO_2 bearing off-gas. The gas is harmful to the environment and must be treated before released to the atmosphere. The gas is cooled, cleaned, and sent to sulfuric acid making.

The chemical reaction of the matte smelting:

$$\mathrm{CuFeS_2} + \mathrm{O_2} \rightarrow (\mathrm{Cu, Fe, S})(matte) + \mathrm{FeO}(slag) + \mathrm{SO_2} \quad (2.1)$$

The stoichiometry varies depending on the level of minerals in the concentrates and the degree of Fe oxidation. Matte smelting is a series of trade-offs where the concentration of Cu is the most important. Larger flow of O_2 results in less Fe sulfide in the matte which generates a higher concentration of Cu. However, too much oxygen results in oxidation of Cu and thus the slag will contain Cu which is unwanted. Due to this phenomenon optimizing oxygen flow is a very important to achieve an acceptable matte grade and a slag that’s low in Cu. (Schlesinger, 2011)

3.4.2 Converting

The next step after the matte smelting process is converting the molten Cu-Fe-S matte to molten “blister” copper. The converting process oxidizes the Fe and S from the matte with oxygen-enriched air. When Fe and S oxidize in the converter, enough heat is generated to make the process autothermal. To further reduce the S and O contents the blister is sent to fire- and electrorefining.

The products of converting are:

- Molten blister copper (99% Cu, 0.02% S and 0.6% O)
- Molten Fe-silicate slag (4 – 8 % Cu), which is sent to Cu recovery.

- SO_2-bearing off-gas which is treated and sent to sulfuric acid production. (Schlesinger, 2011)

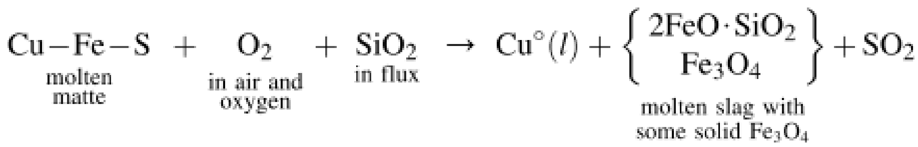


Figure 4. The chemical reaction of the converting process. (Schlesinger, 2011)

3.4.3 Fire refining and casting of anodes

Fire refining is the last step of the pyrometallurgical process of copper before the molten copper is cast into thin flat anodes for electrorefining. Before anode casting is possible, the sulfur and oxygen have to be reduced once again by air oxidation, followed by hydrocarbon reduction in a rotary furnace. If the sulfur and oxygen are not reduced, bubbles will be formed in the cast anodes, making them weak and uneven. The final product of fire refining is molten copper which contains roughly 0.003% S, 0.16% O, at 1200 °C. (Schlesinger, 2011)

The molten copper is cast into 1.2 m x 1.2 m molds on a large rotating wheel resulting in flat thin anodes with a mass of 350 – 400 kg. The uniformity of anode thickness is essential for efficient electrorefining, which is the next step of producing high-purity copper. (Schlesinger, 2011)

3.5 Electrorefining

The first of the two purposes of the electrorefining process is to produce pure copper cathodes free of impurities so the copper can be sold and used in various applications. The second purpose is to separate valuable impurities, such as gold and silver, for recovery. Electrolytic refining is the principal method of producing high-purity copper.

First the anodes and cathodes are put on a rack in an electrolyte cell that is connected to a power supply. The anode starts to dissolve and pure copper begins to plate on the cathodes through a continuous electrochemical process. After 7-10 days of plating the copper cathodes are removed and new empty stainless steel blanks are put in the electrolyte filled cell. One anode produces two or three cathodes and is electrorefined until 80 - 85% is dissolved, a process which takes about three weeks. The anodes are then sent back to be cast again. The impurities with their valuable metals fall to the bottom of the cell and are removed for by-product recovery. (Schlesinger, 2011)

The electrolyte is usually steam heated with hydrocarbon fuel to 60-65 °C to achieve optimal conductivity and mass transfer. In the process it is cooled down about 2 °C.

Schlesinger, 2011 describes the electrorefining process as:

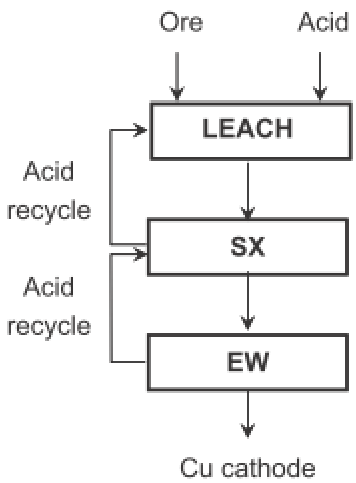
> "An electrical potential is applied between a copper anode and a metal cathode in an electrolyte containing $CuSO_4$ and H_2SO_4. The following process occur:
>
> (a) Copper is electrochemically dissolved from the anode into the electrolyte, producing copper cations plus electrons:
>
> $$Cu^{\circ}_{anode} \rightarrow Cu^{2+} + 2e^{-} \; E^{\circ} = -0.34V \qquad (2.1)$$
>
> (b) The electrons produced by reaction (2.1) are conducted toward the cathode through the external circuit and power supply.
>
> (c) The Cu^{2+} cations in the electrolyte migrate to the cathode by convection and diffusion.
>
> (d) The electrons and Cu^{2+} ions recombine and the cathode surface to form copper metal (without the anode impurities):
>
> $$Cu^{2+} + 2e^{-} \rightarrow Cu^{\circ}_{cathode} \; E^{\circ} = +0.34V \qquad (2.2)$$
>
> Overall, copper electrorefining is the sum of Reactions (2.1) and (2.2):
>
> $$Cu^{\circ}_{impure} \rightarrow Cu^{\circ}_{pure} \; E = 0.0V \text{ "} \qquad (2.3)$$

3.6 Hydrometallurgical copper extraction

Sulfide copper ores are traditionally extracted with concentration, pyrometallurgy and an electrorefining process explained in the chapters above and accounts for 78% of primary copper production. (The World Copper Factbook 2013, 2013)

Oxide copper minerals and chalcocite ores, however, are extracted with hydrometallurgical processes and stand for the remaining 22% of primary copper production (The World Copper Factbook 2013, 2013). According to Schlesinger (2011) the hydrometallurgical process can be categorized into three main operations:

- Leaching, which involves dissolving Cu^{2+}/Cu^{+} from copper ores into a H_2SO_4-H_2O solution, known as the lixiviant, to produce a pregnant leach solution (PLS).
- Solvent extraction (SX) treats the impure PLS to purify and upgrade the solution to produce an electrolyte suitable for electrowinning of copper cathodes.
- Electrowinning (EW), where Cu^{2+} in the purified advance from electrolyte from solvent extraction is reduced to copper metal at the cathode by application of a DC electrical current.



$$Cu_2CO_3(OH)_2 + 2H^+ \rightarrow 2Cu^{2+} + CO_2 + 2H_2O$$

Extraction: $Cu^{2+} + 2RH \rightarrow CuR_2 + 2H^+$

Stripping: $CuR_2 + 2H^+ \rightarrow Cu^{2+} + 2RH$

Cathode: $Cu^{2+} + 2e \rightarrow Cu$

Anode: $H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e$

Figure 5. Simplified hydrometallurgical flow sheet, showing leaching, solvent extraction and electrowinning. (Schlesinger, 2011)

3.6.1 Leaching

Leach heaps are flat around 7 m high and $10^4 – 10^6$ m^2 in the top area. On top of the heap is a network of pipes and sprinklers that trickles the surface with H_2SO_4-H_2O solution. The solution then trickles through the heap, which dissolves the Cu minerals in the copper ore. The Cu-rich pregnant solution (1 to 6 kg Cu^{++}/m^3) is collected thanks to gravity in a pond or tank close to the heap from where it is sent to solvent extraction and electrowinning for copper cathode production. (Schlesinger, 2011)

Underneath the leach heaps there is always an impermeable base, a 1 – 2 mm thick polymer sheet, which prevents the solution from soaking into the underlying environment. The ore is placed on this sheet by either trucks or mobile conveyors, which is the preferred method in Chile. (Schlesinger, 2011)

The ore placed in the heaps can either be run-of-mine (ROM) ore or crushed ore followed by rotating-drum agglomeration. Run-of-mine ore is the cheaper method but the slowest and least efficient. (Schlesinger, 2011)

3.6.2 Solvent extraction

The purpose of solvent extraction is to produce a pregnant leach solution from the leaching. With a more pure solution one can produce high quality copper cathodes with electrowinning. A great advantage of acid leaching and SX/EW is its low costs of low-grade copper ore. (Schlesinger, 2011)

The pregnant leach solution is too dilute and too impure for electrowinning. The Cu^{++} concentration in the electrolyte must reach above 35 kg Cu/m^3 to ensure Cu plating at the cathode surface and to give a high purity copper cathode. The Cu from the impure leach solution must be transferred to the electrolyte and this is done by solvent extraction, which is completed in the extraction and stripping process. The Cu is extracted from the aqueous leach solution into an organic extractant. The Cu is then stripped from this organic extractant into high-H_2SO_4 electrowinning electrolyte. (Schlesinger, 2011)

3.6.3 Electrowinning

The last stage in the SX-EW process is electrowinning and it entails recovering copper from the electrolyte solution produced by the previous process solvent extraction. In electrowinning metal cathodes and inert anodes are put in an electrolyte containing $CuSO_4$ and H_sSO_4. Applying a DC current results in pure copper plating onto the cathodes. The cell voltage needed for EW is about 2.0 V, compared to 0.3 V needed for electrorefining. (Schlesinger, 2011)

The electrolyte from the solvent extraction process contains about 44 kg/m^3 Cu^{++} when it enters the electrowinning cell and contains roughly 5 kg/m^3 Cu^{++} less as it leaves the cell. The electrolyte is then returned to solvent extraction for Cu^{++} replenishment. The electroplating of the cathodes lasts about a week, after which they are stripped from the cathode blanks, washed and sold to the market. (Schlesinger, 2011)

The difference between electrowinning and electrorefining is mainly that the anodes are Pb-alloys instead of copper anodes and that the applied voltage is higher. Compared to electrorefining no precious metal slimes are produced in electrowinning. (Schlesinger, 2011)

Energy requirement for electrowinning is about 2000 kWh/metric ton copper and for electrorefining 300-400 kWh/metric ton copper. The difference is due to voltage requirements (2 volts compared to 0.3 volt for electrorefining). (Schlesinger, 2011)

4 Copper mining industry in Chile

The copper mining industry is very important for Chile's national economy and its share of the country's GDP was 11% year 2013. Total investment in copper mining projects the same year was US$ 9.4bn. (Ocaranza A, 2015)

According to Cochilco, the Chilean copper commission, Chile has been the world's largest copper producer since 1990 (Zeballos, 2013). Almost half of the production is copper concentrate and the majority of exports go to Asia.

The porphyry copper deposits that contain all the valuable copper are often located at high altitudes in the mountains of the Andes. This makes extraction harder as logistics can be problematic and costly. The northern parts of Chile are also very dry and water is a scarce resource, and thus becomes a big problem as copper extraction processes need vast amounts of water. The mine types are most often of the open-pit type but underground mining also occurs.

4.1 Copper production and export in Chile

According to USGS (U.S. Geological Survey) Chile's mine production year 2013 was 5,780 thousand metric tons and total world production was 18,300 thousand metric tons. This makes Chile the world's largest producer of copper and the country accounts for 32% of the world's production. (Mineral Commodity Summaries, 2015).

Table 1. Copper production and export figures for Chile 2013.

	Production (kmt Cu)	Export (kmt Cu)	Export (US$ MN FOB)	Share (%)
Total	5776	5590.1	38596.7	
Codelco	1791.6	1606.7	10911.3	
Other producers	4154.3	3980.7	27669.7	
Mine production	5776			
Smelter production	1358.3			
Refined production	2754.9			
SX-EW cathodes	1935.9			
Electrorefined cathodes	822			
Export by destination				
Europe		723.6	5249.1	14%
America		872.2	6342.4	16%
Asia		3892.8	26197.9	68%
Other		101.5	807.3	2%
Total		5590.1	38596.7	100%
Export by products				
Cathodes		2585	18389.5	46%
Blister		469.8	3597.5	8%
Concentrates		2533.3	16598	45%

kmt = kilo metric tons
Source: Cochilco (2014a)

In Table 1 one can see that the total copper production of 2013 was 5776 thousand metric tons and Codelco’s (National Copper Corporation of Chile) operations account for almost a third of total production. From export by products one can see that 45 % of copper export products are sold as concentrates. The majority of the concentrate is exported to Asia and specifically to China, Japan and India where they have many large smelters and refineries that produce fine copper. The majority of the cathodes exported from Chile are produced with SX-EW methods. The smelters in Chile either sell the blister copper or send it to electrorefineries for further purification. Electrorefineries are often close to the smelters.

Even though Chile’s share of the total world mine production is 32 %, they are only the third largest copper smelter producer at 9 % after China (31 %) and Japan (11 %). The reason for this phenomenon is as stated above that almost half of all mine production is sold as concentrates. Due to the cathode production of SX-EW, Chile is the second largest refined copper producer at 13 % after China (32 %). (The World Copper Factbook 2013, 2013). In Chile there are three electrorefineries: Chuquicamata (600 ktCu/a), Las Ventanas (400 ktCu/a), Salvador (160 ktCu/a). (International Copper Study Group, 2013)

Table 2. Copper production by region 2013.

Region	Production (kmt Cu)
Region I Tarapacá	588
Region II Antofagasta	3048
Region III Atacama	421
Region IV Coquimbo	578
Region V Valparaiso	329
Region VI O´higgins	471
Region VII Maule	-
Region VIII Bio Bio	-
Region IX Araucania	-
Region X Los Lagos	-
Region XI Aysen	-
Region XII Magallanes	-
Region XIII Metropolitan	416
Region XV Arica and Parinacota	0.6
Total	5852

Source: National Geology and Mining Service

In Table 2 it is notable that the northern part of Chile accounts for almost all copper production in the country and the Antofagasta region in particular with more than half of the total mine production. In Figure 6 one can see that SX-EW accounts for roughly one third of the 2013 levels but is expected to decrease over time as new copper mine projects will produce copper concentrates.

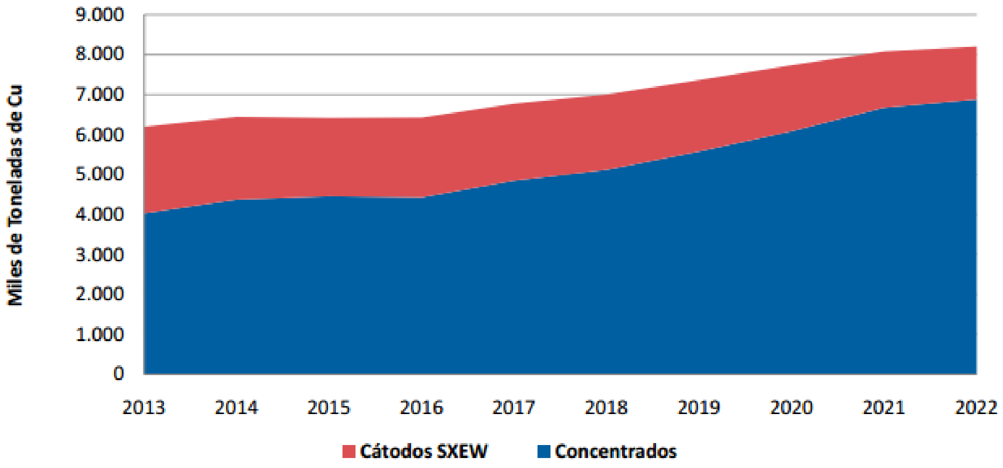


Figure 6. Copper production in Chile by process (SX-EW Cathodes and copper concentrate) 2013 – 2022. (Hernandez, 2014)

4.2 Copper reserves

In a report made by USGS it is claimed that Chile has reserves of 209,000 thousand metric tons. World total reserves are 700,000 making Chile's share of reserves roughly 30%. A 2014 USGS global assessment indicates that known resources contain about 2.1 billion tons of copper and undiscovered resources contain an estimated 3.5 billion tons. (Mineral Commodity Summaries, 2015)

4.3 Ore grades

The average ore grades in Chile have had a significant decline over the years. In figure 6 one can see that the average ore grades have decreased from 1.29% in 2000 to 0.86% in 2012. When looking at ore types, the decrease of sulfides is more pronounced going from 1.38% in 2000 to 0.9% in 2012. The ore grade of oxides has gone from 1.13% to 0.84% in the same time period. One of the impacts of a lower ore grade is the increased fuel needed to haul the ores from the mine as trucks are the most common way of hauling the ore from the mine to the crushers and grinders. When ore grades decrease, hauling has to increase in order to keep the flow of copper at the same level. This results in higher fuel and operation costs.

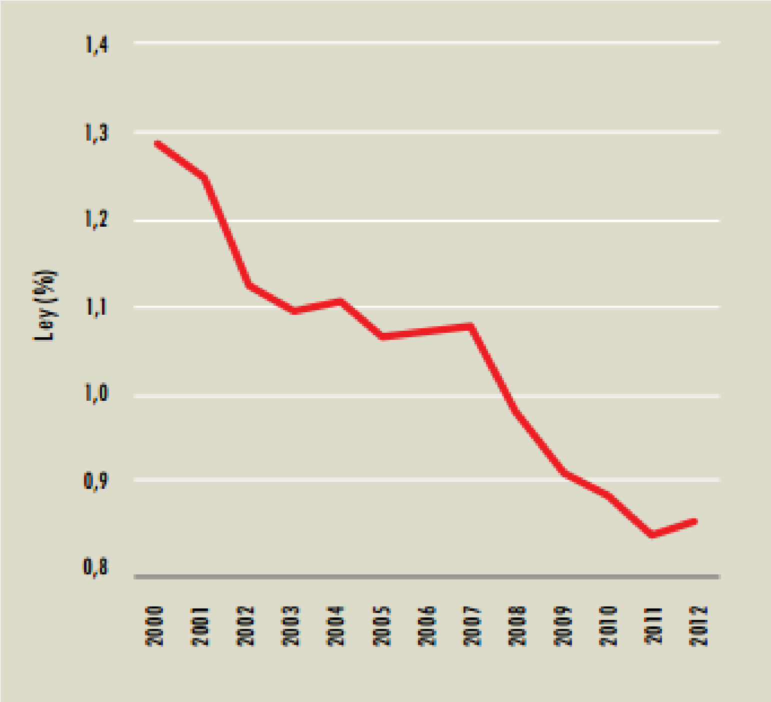


Figure 7. Graph shows the decline of copper ore grade 2000 – 2012. The y-axis represents ore grade. (Cochilco, 2014a)

4.4 Codelco

Chile's state-controlled miner Codelco is considered to be the world's largest producer of copper and controls 10 % of the world reserves of this metal. It is an autonomous company owned by the Chilean state and its main business is the exploration, development and exploitation of copper mineral and byproducts. Codelco develops its operations through six mining divisions plus the Ventanas smelter. (Codelco.com, 2015)

4.5 Copper investment portfolio 2014-2023

According to a report made by Cochilco, they state that 34 new copper projects are in the investment portfolio of 2014, 18 of which are large private mining projects, 6 medium mining projects and Codelco has 6 structural projects. Projects most likely to materialize (base + probable) by companies correspond to 28.3 % of the total portfolio and an equivalent of US$ 29 717 million. The projects that are less likely to materialize (possible + potential) within the deadline indicated by the companies correspond to 71.7% of the portfolio equalling US$ 75 137 million. The total value of the portfolio investment is thus US$ 104 844 million. Worth noting is that the investment portfolio has decreased with roughly US$ 10 million compared to 2013 and it will probably change in the future as projects get postponed or cancelled and new deposits are found or become financially feasible. Of the total portfolio 76.9% was budgeted for copper projects, the rest for gold, silver and iron and other minerals. (Cantallopts, 2014)

If this investment portfolio is materialized the expected total production of copper will in 2023 reach 8.5 million tons, representing a 48% increase to 2013. The majority of copper projects and their share of the investment portfolio will be constructed in the northern regions of Chile – 30% in Antofagasta, 12% in Tarapacá and 11% in Atacama. (Cantallopts, 2014)

Table 3. Investment projects in copper mining 2013 - 2021, Chile.

Operation/Project	Region	Grid connection	State	Status	Start	Type of operation	Type of project
Caserones	Atacama	SIC	Running	Base	2013	Concentrates	New
Caserones	Atacama	SING	Running	Base	2013	SX-EW	New
Ministra Hales	Antofagasta	SING	Running	Base	2014	Concentrates	New
Sierra Gorda conc.	Antofagasta	SING	Running	Base	2014	Concentrates	New
Antucoya	Antofagasta	SING	Running	Base	2014	SX-EW	New
Sierra Gorda Oxidos	Antofagasta	SING	Running	Base	2015	SX-EW	New
Actualizacion Esperanza	Antofagasta	SING	Feasibility	Probable	2015	Concentrates	Expansion
Escondida OGP Phase 1	Antofagasta	SING	Feasibility	Probable	2015	Concentrates	Expansion
Diego de Almagro Sulf.	Atacama	SIC	Feasibility	Possible	2015	Concentrates	New
Diego de Almagro Oxidos	Atacama	SING	Feasibility	Possible	2015	SX-EW	New
El Espino	Coquimbo	SIC	Feasibility	Possible	2016	Concentrates	New
Caspiche	Atacama	SIC	Feasibility	Possible	2016	Concentrates	New
Encuentro Oxidos	Antofagasta	SING	Feasibility	Probable	2016	SX-EW	Reposition
N. Nivem Mina y Otros	O´Higgins	SIC	Feasibility	Probable	2017	Concentrates	Reposition
RT Sulfuros Phase II	Antofagasta	SING	Feasibility	Probable	2017	Concentrates	New
Esperanza sur	Antofagasta	SING	Feasibility	Probable	2017	Concentrates	New
Santo Domingo	Atacama	SIC	Feasibility	Possible	2017	Concentrates	New
Quebrada Blanca Phase II	Tarapacá	SING	Feasibility	Probable	2017	Concentrates	New
Inca de Oro	Atacama	SIC	Feasibility	Possible	2017	Concentrates	New
El Espino Oxidos	Coquimbo	SING	Feasibility	Possible	2017	SX-EW	New
Lomas Bayas III	Antofagasta	SING	Pre-feas.	Possible	2017	Concentrates	New
Tovaku	Coquimbo	SIC	Pre-feas.	Possible	2017	Concentrates	New
Chuquit Subte	Antofagasta	SING	Feasibility	Possible	2018	Concentrates	Reposition
El Abra Mill Project	Antofagasta	SING	Feasibility	Probable	2018	Concentrates	Expansion
Valle Central Expansión	O´Higgins	SIC	Feasibility	Probable	2018	Concentrates	Expansion
Productora	Atacama	SIC	Feasibility	Possible	2018	Concentrates	New
El Morro	Atacama	SIC	Feasibility	Possible	2018	Concentrates	New
Relincho	Atacama	SIC	Feasibility	Possible	2019	Concentrates	New
Cerro Casale	Atacama	SIC	Feasibility	Possible	2019	Concentrates	New
Collahuasi Ampl. Phase II	Tarapacá	SING	Pre-feas.	Possible	2019	Concentrates	Expansion
Encuentro Sulfuros	Antofagasta	SING	Feasibility	Possible	2020	Concentrates	New
Andina Exp. Phase II	Valparaíso	SIC	Feasibility	Possible	2021	Concentrates	Expansion
Los Pelambres Amp.	Coquimbo	SIC	Feasibility	Possible	2021	Concentrates	Expansion

Source: Cochilco, 2013a

5 The electricity situation for the copper mining industry in Chile

The first half of this chapter explains today's electricity situation in Chile and the grid matrix. The second half investigates more deeply into the electricity demand of the copper mining industry and presents estimations of expected electricity consumption in 2025.

5.1 Electricity situation in Chile

Throughout the last ten years, Chile has been through some serious energy supply shortages, including incidents such as a sustained gas supply cut from Argentina (since 2004), a serious drought, and a severe earthquake in 2010 which affected electricity networks and refineries, resulting in major black-outs across Chile. The geography of Chile is unique – it runs 4300 km from north to south and 175 km from east to west. This causes the energy markets of Chile to be regionally disjointed and the regional electricity and gas grids are not connected. In the north, the demand for energy is taken over by the mining industry and its operations are based on the separate Sistema Interconectado Norte Grande (SING) electricity grid. In the central region of Chile which is noticeably more densely-populated, these areas including Santiago operate on the hydro-dependant Sistema Interconectado Central (SIC) electricity grid. In the southernmost region of Chile, the hydro-rich districts of this country are actually not connected to the rest of Chile in regards to the electricity and gas grids. (Oil & Gas Security - Emergency response of IEA Countries, 2012)

According to the report National Energy Strategy 2012-2030 made by Chile's Energy Ministry in 2012 the maximum demand from 2011 was 6881 MW from SIC and 2,162 MW SING. Gross generation from SIC the same year was 46.1 TWh and 15.9 TWh for SING. (Ministerio de Energia, 2012).

It is expected that the growth of the electricity demand will be 6-7 % yearly between 2012 and 2020, which means that total electricity demand will reach almost 100 TWh and the generation supply will increase by more than 8000 MW through new generation projects throughout this period. (Ministerio de Energia, 2012).

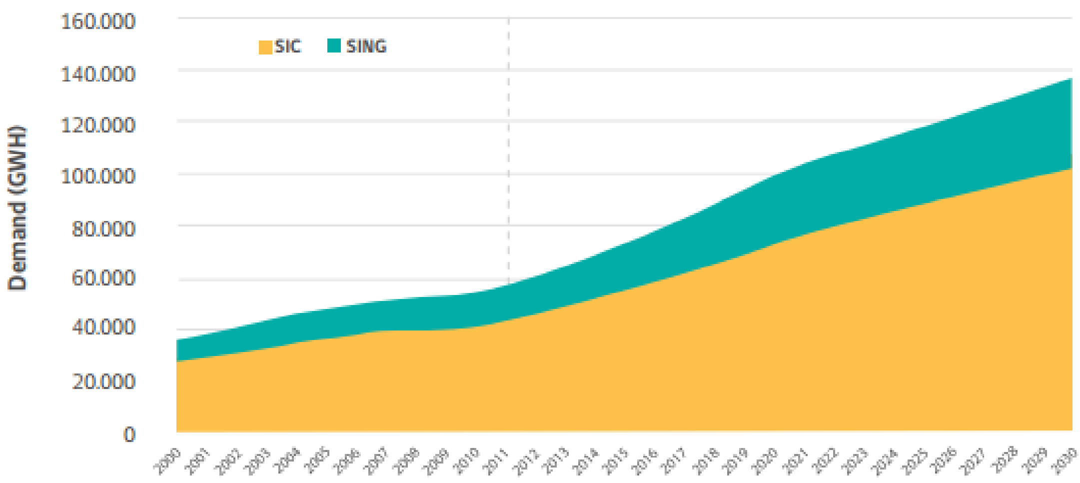


Figure 8. The electricity demand for SIC and SING, 2000 – 2030. (Ministerio de Energia, 2012).

The electricity growth demand is a great challenge for Chile considering that it is importing much of its energy resources and in recent years at high prices, which has resulted in expensive power generation and thus high electricity prices. (Ministerio de Energia, 2012).

The report states that Chile will promote hydroelectricity as well as non-conventional renewable energy (NCRE) resources as part of their commitment to develop renewable energies. However, Chile will still pursue fossil fuels as part of the energy generation as it has high plant factors and competitive costs in comparison to those of other technologies. (Ministerio de Energia, 2012).

Combining the two major grids in Chile, SIC and SING, the current electricity matrix consists of 3 % NCRE, 34 % from hydroelectricity and 63 % from thermoelectricity. By 2024 Chile wants NCRE’s share of the matrix to be 10 % and hydroelectricity 45-48%. (Ministerio de Energia, 2012).

5.2 Argentinian natural gas supply cut

In 1995 Chile and Argentina signed a contract for supply of natural gas through five pipelines from Argentina. From 1995 to 2001, natural gas consumption increased fourfold and replaced much of the coal and oil. Argentina's economic crisis led to a restricted gas export in 2004 which got worse in 2005 and 2006. The gas supply eventually became unsustainable in 2007. After the natural gas crisis Chile had to replace the gas by other imports of fossil fuel. (Toward Energy Security in Chile, 2012)

As a reaction to the natural gas crisis Chile began importing LNG and constructed two terminals – Quintero, which supplies Santiago, and Mejillones, which is located in the Antofagasta region. Both the LNG-terminals are shown in Figure 14. Chile is also considering a third LNG terminal in the central-southern area. However, expensive LNG has restricted the demand for the fuel and coal has become attractive thanks to its cost and availability benefits and in 2012 coal had a share of 27 % for electricity generation. (Toward Energy Security in Chile, 2012)

5.3 The electricity market

The Chilean electricity market is considered flexible and open with most energy projects operating under the traditional independent power producer model. Electricity generators can, since 2008, participate in public tenders under long-term contracts up to 15 years in order to sell power to distribution companies at a fixed price. There is also a "spot" market for power transfers not subject to existing power purchase agreements (PPAs). (Chile's Renewable Energy and Energy Efficiency Market: Opportunities for U.S. Exporters, 2013)

Most power producers in Chile sell their electricity into the wholesale electricity market which is privately operated by only a few large companies, which because of the geography and cost of transmission construction, operate a monopoly. (Chile's Renewable Energy and Energy Efficiency Market: Opportunities for U.S. Exporters, 2013)

5.4 Electricity cost

The price for general consumption has nearly doubled since 2006 from US$ 65/MWh to US$128/MWh in December 2013. The average in SIC was around US$ 112/MWh and US$108/MWh in SING. These prices are among the highest electricity prices in Latin America and the second highest among the mining countries in the world and almost twice the price of competitors such as Peru. (BNamericas, 2014)

5.5 Uncertainty of electricity supply

In the recent years many power generation projects in Chile have failed due to environmental and social factors, which has held back investment in the energy sector and thus risked the development of new mining projects. Chile faces a great challenge if the rejection of power plants continues and the power demand of copper mining increases as anticipated. (BNamericas, 2014)

The first power plant cancellation was in 2010 when GDF Suez had a 540 MW coal-fired plant for the Coquimbo region cancelled by the president as it was in a future environmental protection area. Next was the Castilla project, a 2100 MW thermoelectric plant for the Atacama region. Even though the project had environmental approval it was rejected by the Supreme Court in August 2012 due to an injunction request from the Totoral community and a group of fishermen from Punta Cachos. Codelco had also planned an 800 MW coal-fired plant which was aimed to supply electricity for its operations for Salvador, Andina and El Teniente divisions, but decided to pursue the project. Also in 2011 there was another 300 MW thermoelectric project that had its environmental assessment withdrawn. (BNamericas, 2014)

Not only has it been coal projects that have been rejected by the government but the hydroelectric project HidroAysén was also rejected for environmental reasons. The hydro plant would have had a generation capacity of 2750 MW, enough to supply 21 % of the SIC grid demand. A total of 6350 MW has been rejected in recent years with a total value of US$ 12840 million. (BNamericas, 2014)

5.6 Self-supply of electricity for miners

With the situation of power plants being rejected by the government and communities miners have had to take initiative themselves, where the state owned miner Codelco has been active. As a result the Luz Minera power project will be built in Mejillones, Antofagasta region and will generate 760 MW with a combined cycle gas turbine. The power plant will ensure power supply to Codelco's operations Ministro Hales, Radomiro Tomic, Chiquimata and Gaby divisions. A potential future expansion of 400 MW is also considered for the power plant. Codelco has also another thermoelectric project in its portfolio planned to be constructed in Quintero and be connected to the central SIC grid where it could supply electricity to El Teniente, Andina, Salvador and Ventanas. (BNamericas, 2014)

The mining companies need long-term supply arrangements. One way of securing long term supply agreements is to prepare and obtain permitting for the project and then open a public tender for its construction and maintenance. This is what is called a PPA (power purchase agreement). A PPA lets the mining company sign a long term contract with the generating company, who ensures power supply to a price that does not hurt profitability for the miner. The generating company gets a guaranteed client that ensures that financing and maintenance of the power plant are profitable. (BNamericas, 2014)

Also the Chilean miner Antofagasta PLC has invested in a wind farm, El Arryán, and signed a PPA which will provide approximately 20% of the mine Los Pelambres' electricity over a 20 year period. Antofagasta PLC has also invested in a 530 MW run-of-river hydroelectric project with two 20-year PPA's. (Antofagasta PLC, 2015)

5.7 Electricity consumption of copper mining in Chile 2012

The electricity consumption for copper mining in Chile varies between the regions. Due to more copper mining operations existing in the northern parts of Chile than in the central and southern regions, the northern region will have a higher electricity consumption. The northern region is connected to the SING grid, whereas the central regions including Santiago are connected to the SIC. In Figure 15 one can see the geographic borders for the two grids. Also, the method of copper extraction separates the two grids apart, which has an effect on the electricity consumption. Because of the reasons above, it is common to separate SING and SIC when looking at the electricity consumption, but also look at the country as a whole.

5.7.1 Electricity consumption of copper mining in Chile 2012 – nationwide

Electricity consumption in copper mining has increased from 13.1 TWh in the year 2001 to 21.1 TWh in 2012, equivalent to an increase of 60.5% and an annual growth rate of 4.2%. Looking at the electricity consumption of extraction processes it is notable that copper concentrates production was the largest consumer at 51% and SX-EW (leaching, solvent-extraction, electrowinning) was second largest at 27%. The other process were all under 10% each. The processes that have had the largest increase in electricity consumption is concentrates production, which has seen an increase from 6112 MJ/TMF (ton metric fine copper) to 11071 MJ/TMF, equivalent to an 81% increase. (Cochilco, 2014a)

5.7.2 Electricity consumption of copper mining in Chile 2012 – SING

Electricity consumption of copper mining in the SING has increased from 7.6 TWh to 12.1 TWh in the time period 2001-2012. This is a total increase of 57.9% with an annual growth rate at 4.4%. The largest extraction process consumer in 2012 was SX-EW at 41.7% followed by the concentrates production at 36.8 % and other processes at less than 7%. The mine processes and concentrates production have increased their electricity consumption by

104% and 88% respectively, while SX-EW has not increased significantly in relative terms. In the period 2001 – 2012 the concentrates production saw an energy increase from 5083 MJ/TMF to 9493 MJ/TMF, a total increase of 86.8 %. The reason for the energy increase is partly due to lower ore grades and increasing ore hardness. (Cochilco, 2014a)

5.7.3 Electricity consumption of copper mining in Chile 2012 – SIC

Electricity consumption by copper mining in the SIC has increased from 5.5 TWh in 2001 to 9.0 TWh in 2012, equivalent to a 64.2% increase with an annual growth rate at 4.0%. In the SIC, the largest consumer is concentrates production at 69.2% of total consumption, followed by smelting at 11.3%. The rest of the processes, including SX-EW, consumed less than 8% each. The processes that have had the largest consumption increase over this period is SX-EW, concentrates production and mine operations with an increase of 81%, 77% and 74% respectively. In the case of electricity consumed per metric ton fine copper, the concentrates production has seen an increasing trend from 7331 MJ/TMF to 12537 MJ/TMF between 2001 and 2012. (Cochilco, 2014a)

5.8 Expected electricity consumption of copper mining in Chile 2014 - 2025

The full methodology can be read in Cochilco's report Análisis de Variables Claves para la Sustentabilidad de la Minería en Chile. A short version of the methodology is that the electricity consumption is based on the current operations and projects under construction. The future expected consumption is based on the projects to be built. However, the future projects are uncertain but are estimated on the probabilistic methods that yield lower results than the maximum potential if all projects would be executed without delays in the construction. (Cochilco, 2014a)

5.8.1 Expected electricity consumption of copper mining in Chile 2014 - 2025 – nationwide

In the case of the expected electricity consumption 2014-2025, that considers uncertainty in future projects, Cochilco estimates that total consumption will grow from 21.9 TWh to 39.5 TWh, which represents an increase of 80.6% over the period 2014 – 2025 at an annual growth rate at 5.5%. Furthermore, in the case of maximum consumption of electricity, the consumption could increase to 46.3 TWh in 2025 with a growth rate at 6%. Finally, in the case of minimum power consumption, which is a very pessimistic scenario, Cochilco projects a growth of 4.3% to a total 22.9 TWh in 2025. (Cochilco, 2014b)

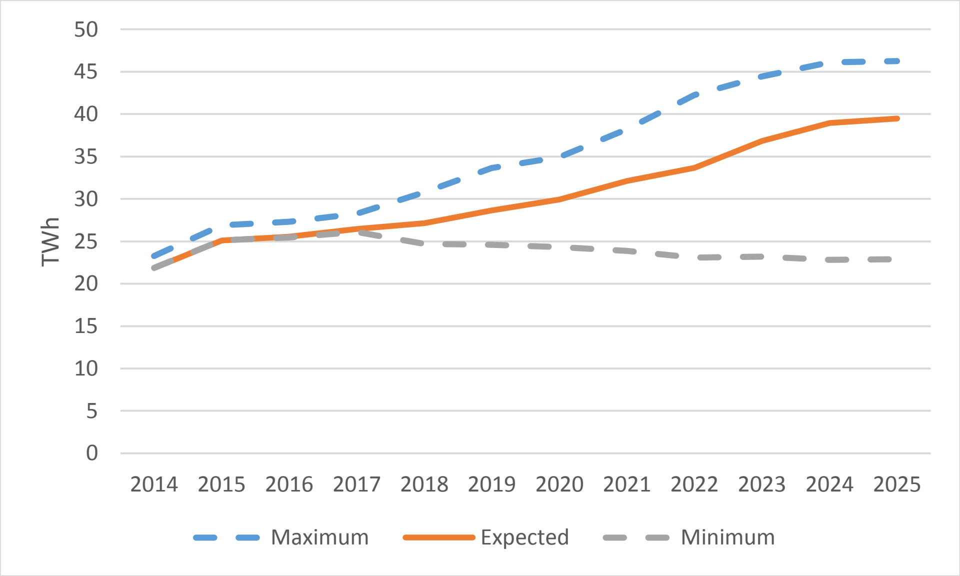


Figure 9. Expected electricity consumption for copper mining industry in Chile 2014 – 2025. (Cochilco, 2014b)

It is estimated, according to the expected consumption of electricity, that in order to meet the expected demand of copper mining, Chile would require adding a power generation capacity of 2500 MW over the period 2015 – 2025, of which 1400 MW are estimated for the SING grid and 1100 MW for the SIC. (Cochilco, 2014b)

5.8.2 Expected electricity consumption of copper mining in Chile 2014 - 2025 – SING and SIC

Copper mining shows great potential for growth in the SING and SIC grids with an estimated annual growth at 5.2% and 6.1% respectively. In 2025 the estimated electricity consumption for copper mining in the SING will be 23.3 TWh and 16.1 TWh in the SIC, which is a total increase of 74% and 91% respectively. (Cochilco, 2014b)

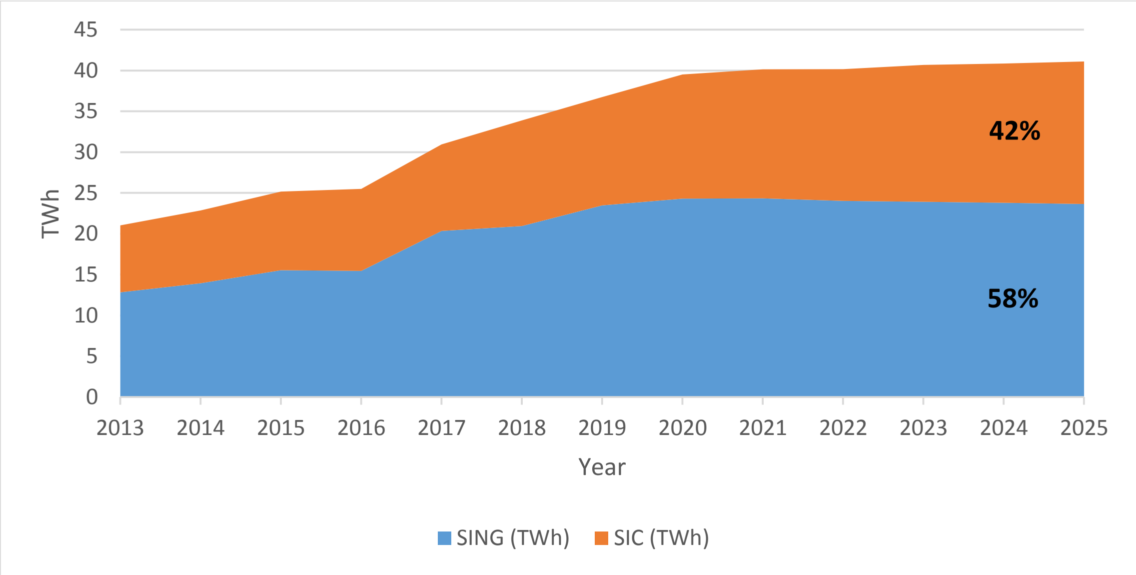


Figure 10. Expected electricity consumption of copper mining for SING and SIC 2014 – 2025. (Cochilco, 2014b)

Within the SING grid, it is mostly the Antofagasta region that will have the increase in demand over the first five years, whereas in 2018-2020 there are also potential projects in the Tarapacá region. In the SIC grid there are large potentials in the Atacama region, which has an estimated growth of 197% from 2.4 TWh to 7.1 TWh. (Cochilco, 2014b)

5.8.3 Expected electricity consumption of copper mining in Chile 2014 - 2025 – by type of project

In Figure 10 one can see that the existing operations shows a steady decline in electricity consumption, expected to decrease 30.6% compared to the levels of 2014. For current operations repositioning or expansion projects, the total increase is 10 TWh in 2025. Adding this number to the current operations would lead to a total electricity consumption of 24.4 TWh, equalling an increase of 18%. The big jump from 24.4 TWh to 39.5 TWh in 2025 would be generated by new projects. (Cochilco, 2014b)

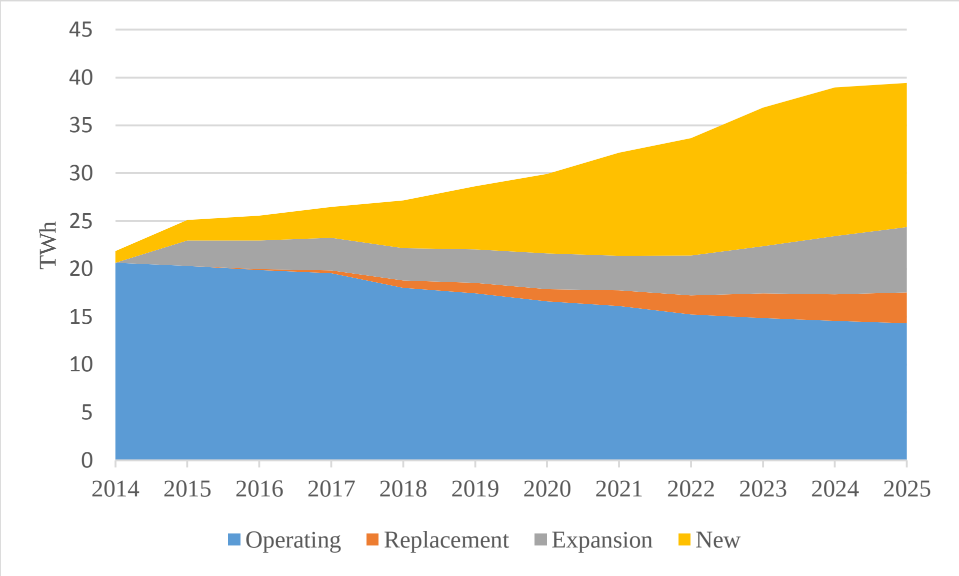


Figure 11. Expected electricity consumption of copper mining in Chile 2014 – 2025 by type of projects. (Cochilco, 2014b)

5.8.4 Expected electricity consumption of copper mining in Chile 2014 - 2025 – by type of process

In the methodology of the report it states that the electricity consumption by processes are based on two assumptions. First, no mining disruptive technological changes affect significantly in the mining process. Second, the unit consumption of electricity by processes is increasing over time due to the deterioration of the geological resource. (Cochilco, 2014b)

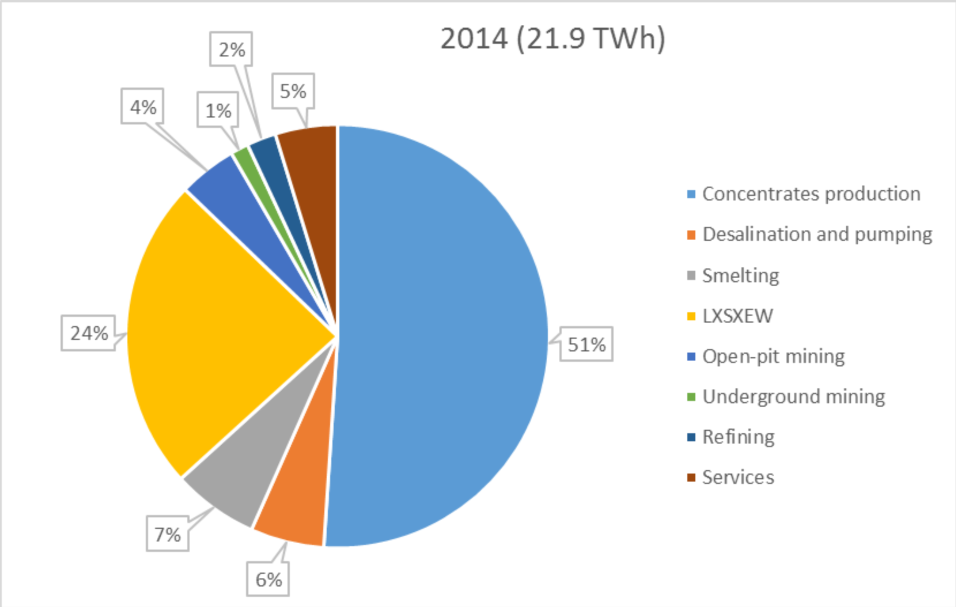


Figure 12. Electricity consumption of 2014 by process and its share of the total consumption. (Cochilco, 2014b)

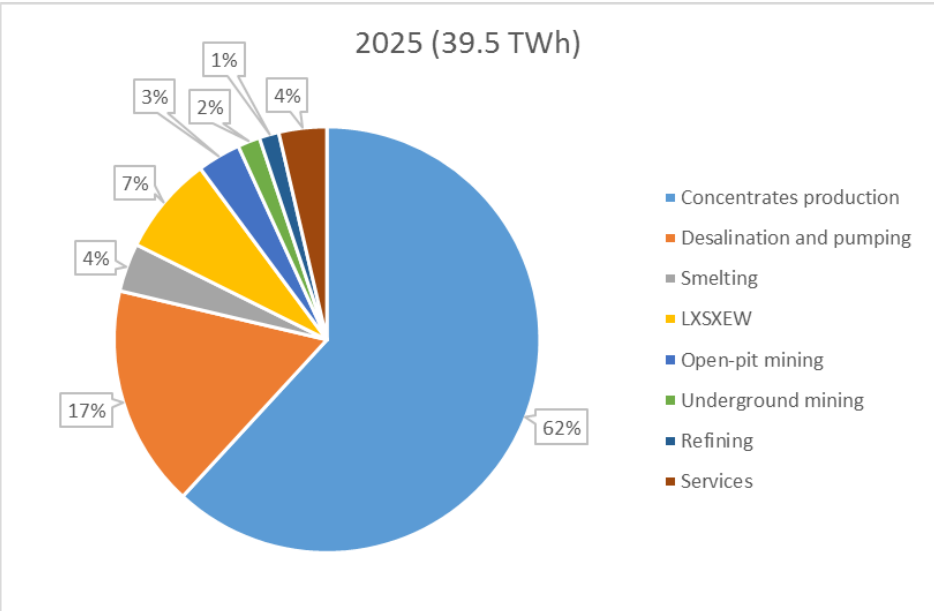


Figure 13. Expected electricity consumption of 2025 by process and its share of the total consumption. (Cochilco, 2014b)

In Figure 12 and Figure 13 one can see that the largest increase of consumption will be from concentrates production, which will increase from 11.2 TWh in 2014 to 24.5 TWh in 2025, representing an increase of 119%. This is a result from the declining ore grades and increasing hardness of the ores. Due to the energy-intensive grinding processes in the concentrates production, the consumption will thus increase. (Cochilco, 2014b)

The second largest increase will be from the desalination and pumping of the desalinated water. This is a consequence of concentrator plants in the northern regions will require vast amounts of water, which is a scarce resource in the region. It is expected that new laws and regulations will require desalinated water for copper mining processes. Due to the mines often being situated in the mountains, the elevation from the sea side up to the copper mines will be high, which has a direct impact of the energy needed to pump the water. (Cochilco, 2014b)

Another important factor is the reduction in total electricity consumption for LXSXEW, which will decrease with 43% in the period 2014 – 2025. This is due to the end of life of various hydrometallurgical operations producing copper cathodes. (Cochilco, 2014b)

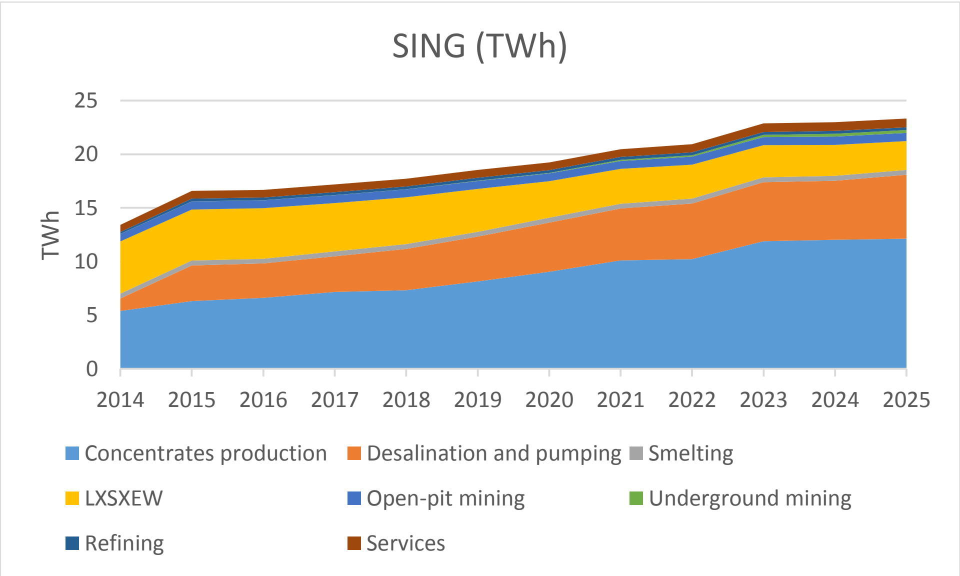


Figure 14. Expected electricity consumption of copper mining 2014 - 2025 in SING by process. (Cochilco, 2014b)

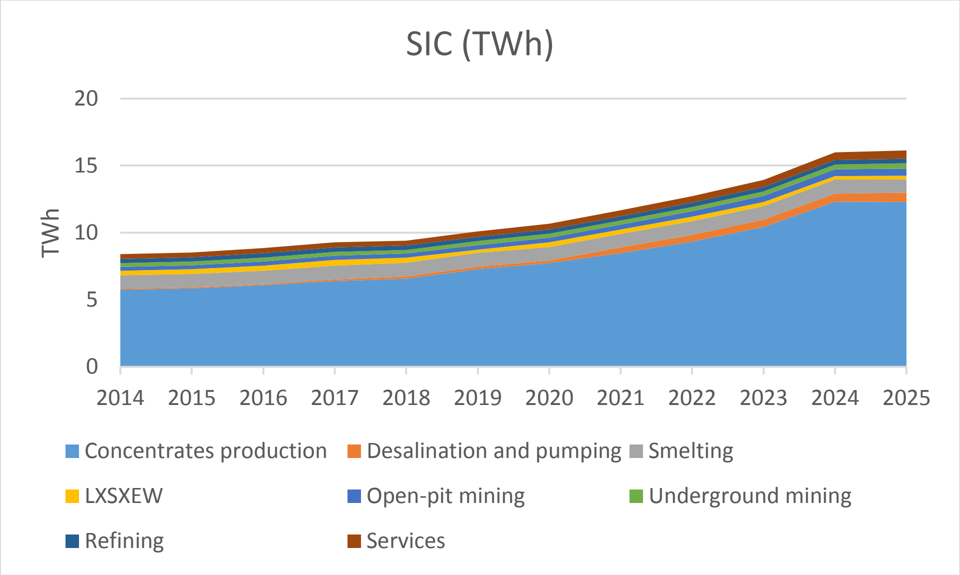


Figure 15. Expected electricity consumption of copper mining 2014 - 2025 in SIC by process. (Cochilco, 2014b)

In Figure 12 and Figure 13 above one can see that the electricity consumption increase of concentrates production occurs for both SING and SIC operations. However, notable is that the desalination and pumping will only see an increase in the SING grid. Since most LXSXEW operations exist in the SING, the reduction of LXSXEW consumption will occur in the SING grid. In the SIC grid basically all increase of the consumption will come from the concentrates production. (Cochilco, 2014b)

5.9 Electricity unit coefficients per metric ton of copper

The expected electricity consumption in 2025 explained in Chapter 5.8 is based on electricity unit coefficients of mining processes. Based on these coefficients and the probability of new copper mining projects, Cochilco have made estimates of electricity consumption to 2025.

One can look at the unit coefficients in two ways – kWh per ton fine copper and kWh per ton material processed. The coefficients vary depending if the operations exists in SING or SIC grid. It is notable that concentrates production and LXSXEW have a higher coefficient in the SIC and underground mining is more energy-intensive in the SING grid.

Table 4. Coefficient units per ton fine copper (kWh/ton fine copper).

Process	SING	SIC	Nationwide
Open-pit mining	172	138	164
Underground mining	977	640	655
Concentrate prodcution	2,637	3,492	3,075
Smelting	1,222	998	1,088
Refining	367	377	373
LXSXEW	2,962	3,483	3,010
Services	219	135	188

Source: Cochilco, 2014a

Table 5. Coefficient units per ton material processed.

Process	SING	SIC	Nationwide
Open-pit mining (kWh/ton mineral extracted)	1.2	1.1	1.2
Underground mining (kWh/ton mineral extracted)	16.1	5.8	6.0
Concentrate prodcution (kWh/ton mineral extracted)	20.2	24.5	22.5
Smelting (kWh/ton mineral processed)	390.6	302.4	336.7
LXSXEW (kWh/ton mineral processed)	11.5	12.2	11.2

Source: Cochilco, 2014a

According to Schlesinger (2011) the total electricity consumption of electrorefining is 300 – 400 kWh per tonne of copper produced. This is in line with Cochilco's coefficients in Table 4.

According to a site visit presentation of the Escondida mine, their two concentrator plants Los Colorados (1990) and Laguna Seca (2002) produce 120 and 110 ktpd (kilo ton per day material processed) with an average monthly electricity consumption of 62 GWh per plant. (BHP Billiton, 2012)

5.10 Electricity demand of desalination plants

The single largest cost of desalination plants is energy, of which 4 MWh is needed for every million litre of fresh water. (Herndon, 2013). When looking at the electricity consumption of desalination there are two main factors to consider. The first one being the electricity needed to desalinate the sea water and the second to pump the desalinated water to the copper concentrator plants that are located in the mountains. According to a report made by Cochilco, the formulas to calculate the electricity needed to desalinate water and pumping of the desalinated water are shown in Table 6.

Table 6. Electricity consumption of desalination of water.

Process	**Power (MW)**
Desalination of sea water	$P(MW) = 4 \frac{kWh}{m^3} \times Q \times 3.6 \frac{MJ}{kWh}$ (5.14)
Pumping desalinated water	$P(MW) = \frac{g \times \rho \times Q \times H}{10^6 \times \eta_{pump} \times \eta_{motor}}$ (5.15)
Annual electricity consumption	$Energy \left(\frac{GWh}{year}\right) = \frac{P \times days \times hours}{10^3}$ (5.16)

Source: Cochilco, 2014b

Where:

- g, gravitational acceleration 9,81 (m/s^2).
- ρ, density of water 1000 (kg/m^3).
- H, altitude (meters above sea level).
- Q, flow of water, (m^3/s).
- η_{pump}, efficiency of pump (%).
- η_{motor}, efficiency of electric motor (%).
- Power, calculated from (7.9) and (7.10)
- Days: 360
- Hours: 20

6 Thermal need for copper mining processes in Chile

In this chapter I will address the thermal needs of copper extraction processes. The thermal need in this chapter refers to any sort of heating for processes or where steam would be a part of a flow sheet.

For optimal electrowinning and electrorefining, the temperature of electrolyte needs to be around 50 – 60 °C according to Schlesinger (2011). The conventional way of heating the electrolyte is with steam, which usually is produced by diesel boilers and heat exchangers. Typical thermal power demand of electrowinning plants are between 5 to 20 MW_{th}. (Roman and Vásquez, 2015)

Table 7. Heat demand of electrolyte heating in electrowinning plants in Chile.

Nº	Mine	Production	Configuration	Number of Cells	Heat Duty
		ton/year			MW
1	Codelco Norte Hidro Norte (Ex RT)	305,000	A-B-C: 2E x 1S x 1W. Train D: 2E x 2S x 1W	1,000	30.8
2	El Abra	225,000	2E x 1W x 1S	680	13.9
3	Escondida	150,000	2E x 1W x 1S	480	9.8
4	Codelco Norte Hidro Sur Óxidos	126,000	Train A: 2E x 2S Train B: 2E x 1S	786	32.3
5	Zaldivar	125,000	2E x 1W x 1S	368	7.5
6	Cerro Colorado	100,000	2E x 1S	420	8.6
7	Quebrada Blanca	79,000	2E x 1S	264	5.4
8	El Tesoro	75,000	2E x 1W x 2S	284	17.6
9	Michilla	64,200	2E x 1W x 2S	208	12.9
10	Mantoverde	62,000	2E x 1W x 2S	168	10.4
11	Lomas Bayas	60,000	2E x 1W x 2S	180	11.1
12	Mantos Blancos	60,000	2E x 1W x 2S	164	10.2
13	Collahuasi	50,000	2E x 2S x 1W	188	3.8
14	Codelco Norte Hidro Sur Sulfuros (Ex Mina Sur)	22,516	2E x 1S	94	1.9

Source: Universidad de Chile, 2009

In Table 7 one can see the heat demands of electrolyte heating for SX-EW plants in Chile. The production rates are at least older than 2009 but are however not far away from today's levels and show a guideline for the heat demand of a typical SX-EW plant. The heat demands varies from 1.9 MW up to 32.3 MW but most plants show a demand of 5 – 15 MW, which is in line with Roman and Vásquez (2015).

The list is taken from a report made by University of Chile in 2009. The report focuses on how solar collectors could be utilized to heat electrolyte for electrowinning. Solar collectors could be placed between the heat exchangers and the boiler in the circuit to reduce the fuel consumption for the boiler, and thus decrease the fuel costs and reduce the CO_2 emissions.

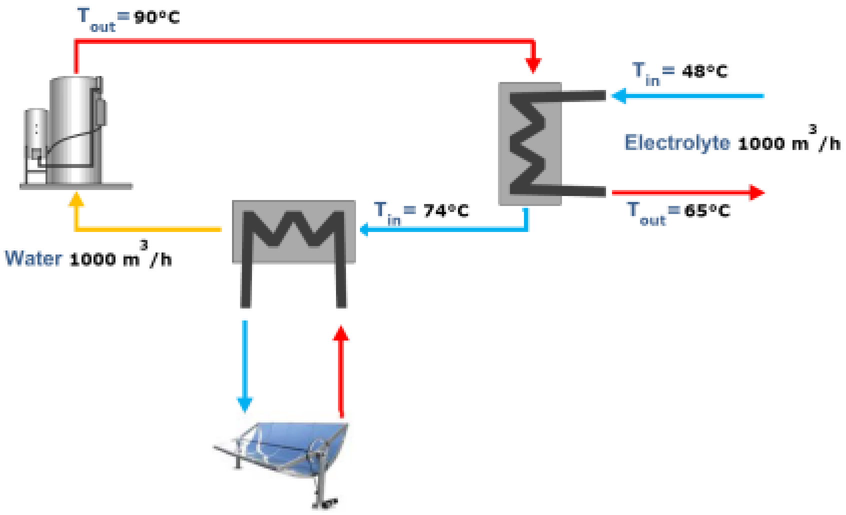


Figure 16. A flow sheet of how solar collectors could be integrated in the process of heating electrolyte. (Universidad de Chile, 2009)

In Table 8 one can see that Codelco's electrorefineries have a heat demand of 35 – 39 MW for heating the electrolyte. The heat source for this process could be hot off-gases from the matte smelters, which often are located close to the electrorefineries. This heat source could be utilized with a heat recovery system to produce steam.

Table 8. Heat demand for electrorefineries in APEC countries. Chuquicamata Refinery and Las Ventanas are owned and operated by Codelco.

Electrorefining Plant	Economy	Production	Number of cells	Heat Requirement
		kTon/year		MW
Amarillo	United States	450	1,430	39.3
Chuquicamata Refinery	Chile	443	1,415	38.9
El Paso	United States	415	1,357	37.3
Guixi	China	400	1,326	36.5
CCR Refinery (Montreal)	Canada	380	1,284	35.3
Pyshma Refinery	Russia	380	1,284	35.3
Las Ventanas	Chile	376	1,276	35.1
Toyo/Niihama (Besshi)	Japan	365	1,253	34.5
Ilo Copper Refinery	Peru	350	1,222	33.6
Jinchuan	China	350	1,222	33.6
Yunnan	China	350	1,222	33.6
Norilsk Refinery	Russia	330	1,180	32.5
Garfield	United States	300	1,118	30.8
La Caridad	Mexico	300	1,118	30.8
Kennecott Utah Cu Magna Utah	United States	280	1,400	38.5
Sumitomo Tokyo	Japan	123	488	13.4

Source: (Universidad de Chile, 2009)

7 Desalination industry in Chile

The copper mining industry uses huge amounts of water for its processes and in the northern dry regions fresh water is scarce. Currently there are no regulations of any specific source of the water in their operations. However, the government is currently reviewing laws that would demand that desalinated water is used for their operations. Due to these laws probably realizing, according to Cochilco, Chilean copper sector's demand for fresh water is expected to grow 38% by 2021, from 13.8 m^3/s to 18.0 m^3/s. (Cochilco, 2013b) (Chile: Desalination Industry Overview, 2014). The desalination process requires a lot of electricity and due to the high altitude of the mine locations, the pumping of the desalinated water also uses a lot of electric power.

The desalination industry will increase the availability of water for miners and allow them to remain competitive in the long term. Desalination will also minimize the potential conflicts between the mining industry and the local communities who also need the freshwater resources. Many miners have already invested in desalination plants to secure their water supply in the future, such as Escondida of BHP Billiton, El Abra of Freeport-McMoRan and Radomiro Tomic and Chuquicamata of Codelco. But many more are planned for the future as the government probably will demand it. In Appendix 3 is a list of planned desalination plants and their electric power demand. (Chile: Desalination Industry Overview, 2014). In 2013 BHP Billiton approved an extension of the desalination plant that will be commissioned in 2017 and be able to desalinate 2.5 m^3/s. (Bhpbilliton.com, 2015)

Year 2013 the copper mining industry in Chile used 12.5 m^3/s freshwater for its operations. The region with largest consumption was the Antofagasta region which used almost 5 m^3/s, roughly three to four times more than other copper producing regions. In 2013 concentration plants used 0.57 m^3/ton mineral processed and hydrometallurgical process SX-EW used 0.09 m^3/ton mineral processed, which shows that concentrates production needs six times more water than SX-EW. (Cochilco, 2013b)

8 Results

One of the main purposes of the thesis was to investigate and explain the following subjects:

- Copper extraction methods and processes (Chapter 3)
- Copper mining industry in Chile (Chapter 4)
- Electricity and thermal power needs of copper mining processes (Chapter 5, Chapter 6, and Chapter 8)
- Desalination industry for copper mining (Chapter 7)

8.1 Interview results

The interviewee was Meshal Ruplal, Engineering VP of AngloAmerican. The reason why I chose Mr Ruplal is because he was a contact of Wärtsilä's from a previous exhibition. AngloAmerican is a global diversified mining business that produces raw materials such as copper, nickel, iron ore, platinum and diamonds. In Chile, AngloAmerican has five copper mines and one smelter, both SX-EW and concentrates production. The interview was conducted by telephone and the questions were prepared. (Appendix 4)

From the interview with Meshal Ruplal I understood that the copper mining industry at the moment is not as good as it was one year ago due to the decrease of the copper price from roughly US$ 3.40/lb. to US$ 2.50/lb. This has made small miners unprofitable and larger mining companies have had to make changes in order to reduce costs. One of the questions asked, was whether there are energy spikes in copper mining processes. Ruplal suggested that energy spikes that do occur, are not large for copper mining processes and that it is not an issue for their company.

When asked about the thermal needs of the copper mining process I was informed that there are no major heat demands except for the electrolyte heating mentioned. Ruplal did not know of any other auxiliary process that needed thermal power either, such as heating of buildings.

In the interview Ruplal explained that AngloAmerican prefers buying electric power from the grid rather than building their own power station. The reasons for this were the high capital investment costs and better financially long-term.

To secure the power supply, AngloAmerican constantly negotiate with their electricity supplier. For all their operations they have power purchase agreements which are in place for 20 years, which has been an increasing trend in the mining industry. However, mines located further away from the electric grid have their own power station in order to secure their power supply.

My last question of the interview was the community’s view on LNG and HFO as fuel for power generation, which Ruplal said that is fairly positive in Chile.

8.2 Map of operating mines in Chile

Figure 14 illustrates the geographic location of operating copper mines and smelters in Chile, from Cerro Colorado in the north to El Teniente in the south. Additionally, the map also shows SING and SIC geographic spread over the country as well as the regions of Chile. Chile’s two LNG terminals are also marked with stars, Mejillones in the Antofagasta region and Quintero in the Valparaíso region. On the map one can see that almost half of the copper mining operations occur in the Antofagasta region. On the map there are 35 copper mines and smelters, however in Appendix 2 there are 42 totally. This is due to not being able to find the location of some mines.

Figure 17. Map of operating copper mines and smelters in Chile.
(Consejominero.cl, 2015b)

8.3 Total electricity unit coefficient of copper mining operations

To calculate the total electric energy demand of copper mines one has first to add the electricity unit coefficients together for both concentrates and SX-EW production, SING and SIC separately (Table 4). I have not calculated the electric energy demand for smelters and electrorefineries since there are only three of them in Chile and there are no new projects at the moment. For mines that have both open-pit and underground mining I have assumed that the share of underground mining accounts for 50% of the total mine production, if I have not found a source suggesting differently. The formulas below are used for Appendix 1, which is a table showing facts for operating mines in Chile and their electric energy consumption.

- Concentrates, SING: Open-pit mining + concentrates production + services
  - $(172 + 2637 + 219)\frac{kWh}{tCu} = 3028\ \frac{kWh}{tCu}$ (8.1)

- Concentrates, SING: Open-pit & underground mining + concentrates production + services
  - $\left((172\ \times 0.5 + 977\ \times 0.5) + 2637 + 219\right)\frac{kWh}{tCu} = 3431\ \frac{kWh}{tCu}$ (8.2)

- Concentrates, SIC: Open-pit mining + concentrates production + services
  - $(138 + 3492 + 135)\frac{kWh}{tCu} = 3765\ \frac{kWh}{tCu}$ (8.3)

- Concentrates, SIC: Open-pit & underground mining + concentrates production + services
  - $(138\ \times 0.5 + 640\ \times 0.5) + 3492 + 135)\ \frac{kWh}{tCu} = 4016\ \frac{kWh}{tCu}$ (8.4)

- Concentrates, Nationwide: Open-pit mining + concentrates production + services
  - $(164 + 3075 + 188)\ \frac{kWh}{tCu} = 3427\ \frac{kWh}{tCu}$ (8.5)

- Copper anodes, SING: Smelting
  - $1222\ \frac{kWh}{tCu}$ (8.6)

- Copper anodes, SIC: Smelting (8.7)

  - $998 \frac{kWh}{tCu}$

- Electrorefined cathodes, SING: Smelting + refining
  - $(1222 + 367)\frac{kWh}{tCu} = 1589 \frac{kWh}{tCu}$ (8.8)

- SX-EW, SING: Open-pit mining + LXSXEW + services
  - $(172 + 2962 + 219)\frac{kWh}{tCu} = 3353 \frac{kWh}{tCu}$ (8.9)

- SX-EW, SIC: Open-pit mining + LXSXEW + services
  - $(138 + 3483 + 135)\frac{kWh}{tCu} = 3756 \frac{kWh}{tCu}$ (8.10)

- SX-EW, Nationwide: Open-pit mining + LXSXEW + services
  - $(164 + 3010 + 188)\frac{kWh}{tCu} = 3362 \frac{kWh}{tCu}$ (8.11)

8.4 Electricity demand of operating copper mines

When the total electricity unit coefficient for each operation has been calculated one needs to know the annual mine production of the operation in question. The mine production rates are taken from ICSG's report Directory of Copper Mines and Plants, 2013. Some are taken from the owner's website. Therefore the production rates are not from the same year and can vary a bit from today's levels.

$$Electricity\ demand\ \left(\frac{GWh}{year}\right) = \frac{Mine\ production\ \left(\frac{ktCu}{year}\right) \times tot.el.coeff. \left(\frac{kWh}{tCu}\right)}{10^3} \quad (8.12)$$

To calculate the size of the power plant needed to meet the electricity demand of the mining operations I have assumed that the mining operations would be running 8000 h annually, which includes service stops and other stops that might occur.

$$Power\ (MW) = \frac{Electricity\ demand\ (\frac{GWh}{year})\ \times 10^3}{8000h} \tag{8.13}$$

8.5 Electricity consumption of copper mining processes in Chile

Appendix 1 shows facts for operating copper mines in Chile and the estimation of the mine's total electricity consumption. It is calculated using formulas (8.1) – (8.12) and the constant electric power needed is calculated with (8.13). The table also shows the thermal heat demand for those SX-EW plants listed in Table 7.

Appendix 1 shows the following facts and estimations:

- Mine name, region, owner, start-up year, grid (SING or SIC)
- Mine type (Open-pit, underground or smelter), process (SX-EW, concentrates, copper anodes or electrorefined cathodes), and annual production
- Electric energy demand (GWh/a), power plant size needed (MW), heat duty for some SX-EW plants (MW)

Appendix 2 is a categorization of operating copper mines from Appendix 1 by the electric power demand. The copper mines were organized into four categories: 1 – 20 MW, 20 – 50 MW, 50 – 120 MW, and > 120 MW. Table 9 shows the summary of Appendix 2 and one can see from the table that most copper mines occur in the category of 1 – 50 MW and especially in 1 – 20 MW with totally 15 mines. The category with lowest electric energy consumption is fairly evenly distributed between SX-EW and concentrates production. However, in the 20 – 50 MW category SX-EW occurs more than concentrates production.

In Appendix 2, the copper mines that have both concentrates production and SX-EW, are considered as one mine and its electric energy consumption is a sum of its processes' consumptions.

Table 9. Categorization of electric power demand of operating copper mines in Chile. Summary of Appendix 2.

Electrical power demand (MW)	0 - 20	20 - 50	50 - 120	> 120
Concentrates	6	0	3	2
SX-EW	7	5	4	1
SX-EW/conc.	1	4	2	4
Smelter	2	1	1	1
Total	15	10	10	7

In the interview with Ruplal, he mentioned that the electric energy consumption for the SX-EW plant in Los Bronces mine was 20 MW. From Appendix 1, using Cochilco's electricity coefficient units (Chapter 5.9 and Table 4), one can see that the electric energy consumption estimation is 21 MW, which backs up Ruplal's statement.

8.6 Electricity consumption of a concentrator plant

The total electricity consumption for Escondida's two concentrator plants, Los Colorados and Laguna Seca with a capacity of 120 and 110 ktpd respectively, using Cochilco's unit coefficients for concentrates production of 20.2 kWh/ton (SING) would be (Table 5):

$$(120 + 110)\ \frac{kt}{day} \times 20.2 \frac{kWh}{t} * 30\ days \times 10^{-3} = 139.4\ GWh$$

In the report by BHP Billiton, 2012, Escondida had a total electricity consumption of 124 GWh, which is 11% less in comparison to the result above. This difference seems reasonable as the consumption of concentrator plants varies depending on the state of the technology when it was built.

8.7 Electricity demand for desalination

Appendix 3 shows the electricity consumption for desalination and pumping plants for copper mines in Chile and it is calculated with (5.14), (5.15) and (5.16). The power needed varies depending on the desalinated water flow and the altitude at which the mines operate. In many cases the power needed for pumping is as large as or even larger than the desalination process. Eight out of 16 desalination projects needed less than 10 MW of electric power. Above 10 MW it is quite scattered, but the largest power consumer at 83.9 MW, will be Escondida's plant that will have the capacity to desalinate 2.5 m^3/s.

9 Summary

The main purpose of this thesis was to investigate the copper mining industry in Chile and explain the copper extraction processes and present their electricity and thermal power needs. The secondary purpose was to suggest how Wärtsilä's power plant solutions could be a viable opportunity for the copper mine owners in Chile.

In order to reach these goals I have studied academic research alongside governmental and local reports from Chile. This data has given me a deeper insight into the current copper mining industry and the processes in use. In addition to primary research I have also conducted an interview with Meshal Ruplal who is involved in the copper mining industry in Chile.

9.1 Future challenges for copper mining industry in Chile

The copper mining industry in Chile faces many challenges in the future in order to sustain its competitiveness. Based on the information and research gathered for this thesis, the summary below explains the main challenges Chile faces in the future.

- Geological conditions
  - Lower ore grades, increasing ore hardness, deeper mines, and longer hauling distances all make it harder to achieve good profitability for miners in Chile.

- Communities
    - Environmental awareness of the Chileans has resulted in many power generation projects being cancelled over the recent years. If the rejection of power plants continues, it has the risk of slowing down the development of new copper mining projects. Additionally if the power demand of copper mining increases as anticipated, Chile faces a great challenge.

- Copper price
    - Low copper prices that occur at the moment result in small miners becoming unprofitable and larger companies have to reduce costs to stay competitive. Lower profitability can also have an effect on the investment portfolio resulting in fewer investments.

- Water management
    - New laws and regulations force mine operators to use desalinated water for their processes. The investment costs for desalination plants are large and the electrical energy demand of pumping large amounts of water up to the Andes results in higher operating costs for the copper miners.

- Energy management
    - According to Cochilco, the electricity consumption of the copper mining industry in Chile will reach 39.4 TWh by 2025, which is an increase of roughly 100 % from 2014 levels. The largest share of this growth will be from new concentrator and desalination plants.

9.2 My personal suggestions

One of the purposes of this thesis was to give my personal suggestions for how Wärtsilä’s power plant solutions would be a viable opportunity for mine owners in Chile. Based on the previous chapters and results I will present my personal suggestions in this chapter.

Chile is the largest producer of copper in the world and has been since 1990. One of the main reasons for this, is simply that Cu-rich porphyry copper deposits exists in the Andes. Much of the copper has already been extracted, but there are still huge amounts left as Chile has the largest copper reserves in the world.

The copper market price is always fluctuating and prices go up and down, but the demand for copper in the future will likely not decrease, and for that reason, copper will still need to be mined. Recycling of scrap copper is increasing but won't be enough to meet the market demand, and therefore more mining of primary copper will be needed.

As a result of this, as Chile has vast reserves of copper, the mining industry is highly likely to grow, as Cochilco also predicts. Due to copper extraction being very energy-intensive, many new power plants will be a necessity to meet the already high demand for electric energy in Chile. In the following years leading up to 2025, Cochilco has estimated that 1400 MW will have to be installed in SING and 1100 MW in SIC in order to meet the demand of future copper mine projects.

When taking into consideration all of the factors above, this strongly suggests that the copper mining industry in Chile is likely to grow, and in this growth, will require more new power plants to be built. Therefore, the copper mining industry in Chile is a great business opportunity for Wärtsilä Power Plants.

9.2.1 Wärtsilä CHP solution for electrolyte heating in SX-EW plants and electrorefineries

One of the aims was to investigate the thermal power needs of copper mining processes. The largest thermal power demand is for electrolyte heating for both SX-EW and electrorefineries. This thermal power demand of heating electrolyte would be a good opportunity for Wärtsilä to promote their CHP solutions.

Wärtsilä could utilize the hot exhaust gases from their reciprocating engines to produce steam or hot water, in order to pre-heat the electrolyte in the same way as the solar collectors are intended to do in Figure 13. To transfer the heat from the hot exhaust gases Wärtsilä could use heat recovery systems. This is a proven method and exists in many Wärtsilä power plant solutions, where steam is produced for fuel heating or to feed a steam turbine.

With a CHP solution, the mine owners would decrease their fuel costs for the electrolyte heating, thus also decreasing their operation costs. From an environmental aspect, it is also beneficial as savings in fuel mean less CO_2-emissions.

The SX-EW plants that have a constant electric power demand of 1 – 20 MW and 20 – 50 MW (Appendix 2) would be suitable for Wärtsilä, as the thermal power generated in the heat recovery system is in the same range as the thermal power demand of the SX-EW plants and electrorefineries.

One issue with this opportunity, however, is the decreasing copper production of SX-EW plants in the future as shown in Chapter 5. Some plants are expected to shut down and new copper mining projects will be of concentrates production, and thus the opportunities will decrease by time.

Due to the export of copper concentrates to electrorefineries abroad, Chile does not have many electrorefineries and the potential is thus smaller than electrolyte heating for SX-EW plants. However, it should not be neglected as an opportunity.

9.2.2 Other personal suggestions

Due to the uncertainty of Chile’s electricity generation, mine owners are taking new measures in order to secure their supply of electricity. Mine owners are investing in their own power stations and signing long term power purchase agreements that will provide secure electricity for their operations for many years to come. Every copper mine project is unique and its electricity supply arrangements are different.

At the moment, Chile is investing in NCRE such as wind and solar power. And due to uncertainty of the availability of these energy resources, Wärtsilä's strategy Smart Power Generation, would fit well in Chile's grid matrix to increase grid flexibility and efficiency. Chile has two LNG terminals, Mejillones in the Antofagasta region, where roughly half of the country's copper is mined, and Quintero in the Valparaíso and Metropolitan region. As LNG plays an important role in the country's electricity generation matrix, Wärtsilä could promote their gas engines, or dual-fuel engines for increased fuel flexibility.

Another opportunity for Wärtsilä could be smaller copper mines where access to the grid is not possible. These mines need their own power plant and Wärtsilä could look into this market. Unfortunately, through primary the research that I have conducted for this thesis, it has not been possible to find access to information about these smaller copper mines.

9.3 Further research

As stated in the delimitation I have not investigated into copper mining in Peru or gold and silver mining in Chile or Peru, and therefore these could all be examples of future research.

Another topic of research would be to investigate into the market of smaller copper mines that are far from the grids and thus require self-supply of electricity. To get good results for this one would need to interview key persons as there is not much previous research done.

10 Conclusion

Prior to this thesis I had very little knowledge in the area of mining and copper mining in particular. I feel that the research that I have undertaken in order to write this thesis has given me a deep insight into the copper mining industry in Chile and the country's electrical energy challenges.

In addition to obtaining academic information I feel that I have also learned how to conduct a piece of independent research of this size. With this I understand the importance of self-discipline and how to plan my time and be consistent in order to meet my milestones.

Therefore from this piece of work I feel that I have grown academically and personally.

11 References

Antofagasta PLC, (2013). *Antucoya site visit.* Available at: http://www.antofagasta.co.uk/~/media/Files/A/Antofagasta/reports-and-presentations/analyst-site-visit-dec13/analystvisit-antucoya-site-visit.pdf [Accessed 4 Mar. 2015].

Antofagasta PLC, (2015). *Annual Report and Financial Statements 2013*. [online] London: Antofagasta PLC. Available at: http://www.antofagasta.co.uk/~/media/Files/A/Antofagasta/pdf/annual-reports/ar-2013.pdf [Accessed 23 Feb. 2015].

Bhpbilliton.com, (2015). *BHP Billiton | BHP Billiton Approves Escondida Water Supply Project*. [online] Available at: http://www.bhpbilliton.com/home/investors/news/Pages/Articles/BHP-Billiton-Approves-Escondida-Water-Supply-Project.aspx [Accessed 23 Feb. 2015].

BHP Billiton, (2012). *Escondida Site Tour*. [online] Available at: http://www.bhpbilliton.com/home/investors/reports/Documents/2012/121001_Escondida%20Site%20Visit%20Presentation.pdf [Accessed 26 Feb. 2015].

BHP Billiton, (2015). *Escondida open-pit mine located in Northern Chile*. [image] Available at: http://www.bhpbilliton.com/home/investors/imagegallery/Pages/default.aspx?category=locations&imagedetail=59 [Accessed 24 Feb. 2015].

BNamericas, (2014). *Powering Chile's Mines: An Industry On The Brink*. Mining Intelligence Series. Santiago: BNamericas.

Cantallopts, J. (2014). *CARTERA DE PROYECTOS DE INVERSIÓN MINERA 2014 - 2023*. Available at: http://www.cochilco.cl/archivos/presentaciones/20140826130400_PROYECTOS.pdf [Accessed 23 Feb. 2015]

Chile: Desalination Industry Overview. (2014). 1st ed. [ebook] U.S. Embassy Mining & Energy Team. Available at: http://www.kallman.com/shows/exponor_2015/pdfs/Desalination%20Industry%20Overview%20v4.pdf [Accessed 23 Feb. 2015].

Chile's Renewable Energy and Energy Efficiency Market: Opportunities for U.S. Exporters. (2013). 1st ed. [ebook] International Trade Administration. Available at: http://export.gov/build/groups/public/@eg_main/@reee/documents/webcontent/eg_main_059190.pdf [Accessed 22 Feb. 2015].

Cochilco, (2013a). *INVERSIÓN EN LA MINERÍA CHILENA Cartera de Proyectos 2013 - 2021*. Available at: http://www.cochilco.cl/descargas/estudios/tematico/inversion/INVERSIONES_MIN_2013.pdf[Accessed 2 Mar. 2015].

Cochilco, (2013b). *RECURSOS HÍDRICOS EN LA MINERÍA DEL COBRE*. [online] Santiago: Cochilco. Available at: http://www.cochilco.cl/archivos/presentaciones/20140729171419_Presentacion_Agua_IFT_Energia_y_Agua_Antofagasta.pdf [Accessed 23 Feb. 2015].

Cochilco, (2014a). *Análisis de Variables Claves para la Sustentabilidad de la Minería en Chile*. Santiago. Available at: http://www.cochilco.cl/descargas/estadisticas/recopilacion/2014.pdf [Accessed 2 Mar. 2015].

Cochilco, (2014b). *Proyección del consumo de electricidad en la minería del cobre 2014 - 2025.* Available at: http://www.cochilco.cl/descargas/estudios/informes/energia/proyeccion_consumo_electricidad_2014-2015.pdf [Accessed 2 Mar. 2015].

Codelco, (2014). *Resultados Codelco Año 2013.* Available at: http://www.codelco.com/prontus_codelco/site/artic/20140328/asocfile/20140328120619/resultadoscodelco_2013.pdf [Accessed 4 Mar. 2015].

Codelco.com, (2015). *CODELCO - Corporación Nacional del Cobre, Chile La Corporación*. [online] Available at: http://www.codelco.com/la-corporacion/prontus_codelco/2011-06-21/164601.html [Accessed 23 Feb. 2015].

Consejominero.cl, (2015a). Available at: http://en.consejominero.cl/freeport-mcmoran-copper-gold-2/ [Accessed 4 Mar. 2015].

En.consejominero.cl, (2015b). *Consejo Minero | Mining map*. [online] Available at: http://en.consejominero.cl/about-us/mining-map/ [Accessed 7 Mar. 2015].

Copper.org, (2015). *Copper Production*. [online] Available at: http://www.copper.org/education/copper-production/) [Accessed 22 Feb. 2015].

Doebrich, J. (2009). *Copper—A Metal for the Ages*. 1st ed. [ebook] Reston: U.S. Geological Survey. Available at: http://pubs.usgs.gov/fs/2009/3031/FS2009-3031.pdf [Accessed 22 Feb. 2015].

Extraction and beneficiation of ores and minerals. (1994). Technical resource document, [online]. Available at: http://www.epa.gov/osw/nonhaz/industrial/special/mining/techdocs/copper/copper1a.pdf [Accessed 22 Feb. 2015].

Fcx.com, (2015). *Drilling & Blasting*. [online] Available at: http://www.fcx.com/resources/fmi/drilling.html [Accessed 2 Mar. 2015].

HERNÁNDEZ, S. (2014). *NECESIDADES FUTURAS DE ENERGÍA PARA EL SECTOR MINERO*. Available at: http://www.cochilco.cl/archivos/presentaciones/necesidades_futuras_de_energia_para_el_sector_minero.pdf [Accessed 25 Feb. 2015].

Herndon, A. (2013). *Energy Makes Up Half of Desalination Plant Costs: Study*. [online] Bloomberg.com. Available at: http://www.bloomberg.com/news/articles/2013-05-01/energy-makes-up-half-of-desalination-plant-costs-study [Accessed 26 Feb. 2015].

International Copper Study Group, (2013). *DIRECTORY OF COPPER MINES AND PLANTS up to 2017*. [online] Available at: http://www.icsg.org/index.php/component/jdownloads/finish/166-other/1575-icsg-directory-of-mines-and-plants-2011-03?Itemid=0 [Accessed 27 Feb. 2015].

Mineral Commodity Summaries. (2015). U.S. Geological Survey. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/copper/mcs-2015-coppe.pdf [Accessed 22 Feb. 2015].

Ministerio de Energia, (2012). *NATIONAL ENERGY STRATEGY 2012-2030*. Available at: http://kallman.com/shows/iftenergy_2012/pdfs/Energy-for-the-Future-Chile%27s-National-Energy-Strategy-2012-2030-English.pdf [Accessed 2 Mar. 2015]

Ocaranza A., J. (2015). *Anuario de Estadísticas del Cobre y Otros Minerales*. 1st ed. [ebook] Santiago de Chile: Cochilco. Available at: http://www.cochilco.cl/descargas/estadisticas/anuarios/AE2014.pdf [Accessed 22 Feb. 2015].

Oil & Gas Security - Emergency response of IEA Countries. (2012). 1st ed. [ebook] Paris: International Energy Agency. Available at: http://www.iea.org/publications/freepublications/publication/Chile_2012.pdf [Accessed 22 Feb. 2015].

Roman, R. and Vásquez, J. (2015). *Solar Cogeneration: Integration between Energy and Mining*. Available at: https://www.ises.org/fileadmin/user_upload/PDF/ISES_Webinar_Roman_SolarCogen-30Jan2014.pdf [Accessed 2 Mar. 2015].

Rosenqvist, T. (2004). *Principles of extractive metallurgy*. 2nd ed. Trondheim: Tapir academic press.

Schlesinger, M. (2011). *Extractive metallurgy of copper*. 5th ed. Amsterdam: Elsevier.

Teck. (2014). *Annual report 2013.* Available at: http://www.teckannualreport.com/teckar2013/downloads/Teck-2013-Annual-Report.pdf [Accessed 4 Mar. 2015].

The World Copper Factbook 2013. (2013). 1st ed. Lisbon: International Copper Study Group.

Toward Energy Security in Chile. (2012). 1st ed. Washington DC: Americas Society and Council of the Americas. Available at: http://www.as-coa.org/files/TowardEnergySecurityInChile.pdf [Accessed 22 Feb. 2015].

Universidad de Chile, (2009). *DEVELOPMENT OF THE SOLAR THERMAL MARKET IN THE APEC ECONOMIES*. [online] Santiago. Available at: http://solarthermalworld.org/sites/gstec/files/development_of_the_solar_thermal_market_in_the_apec_economies.pdf [Accessed 23 Feb. 2015].

Wartsila.com, (2015). *About Wärtsilä*. [online] Available at: http://www.wartsila.com/en/about/company-management/overview [Accessed 2 Mar. 2015].

Zeballos, J. (2013). *Challenges facing the mining industry*. Available at: http://www.cochilco.cl/archivos/presentaciones/20130408105755_2013%2003%2012%20-%20Challenges%20facing%20the%20mining%20industry%20%28Chile-Denmark%29%20VF.pdf [Accessed 25 Feb. 2015

Appendices

Appendix 1 Operating mines in Chile (1/3)

Mine	Region	Operator/Owner(s)	Start up	Mine type	Process	Production (thousand metric tons)	Electrical grid	Electricity demand (GWh/a)	Constant electricity demand (MW) (8000 h/a)	Heat demand, MW_{th}	Source
Altonorte	Antofagasta	Glencore	1993	Smelter	Copper anodes	309	SING	378	47		(Consejominero.cl, 2015)
Andacollo	Atacama	Teck Resources Ltd 90%, ENAMI 10%	1996	Open-pit	Concentrates	77	SIC	290	36		(Teck, 2014)
Andacollo	Atacama	Teck Resources Ltd 90%, ENAMI 10%	1996	Open-pit	SX-EW	4	SIC	15	2		(Teck, 2014)
Andina	Valparaíso	Codelco	1970	Open-pit/underground	Concentrates	237	SIC	952	119		(Codelco, 2014)
Antucoya	Antofagasta	Antofagasta	2015	Open-pit	SX-EW	85	SING	285	36		(Antofagasta PLC, 2013)
Candelaria	Atacama	Freeport-McMoRan Copper & Gold Inc. (80%), Sumitomo Metal Mining (l5%), Sumitomo Corp. (5%)	1994	Open-pit	Concentrates	168	SIC	633	79		(Consejominero.cl, 2015)
Caserones	Atacama	Pan Pacific Copper 75%, Mitsui 25%	2014	Open-pit	Concentrates	150	SIC	565	71		(Consejominero.cl, 2015)
Caserones	Atacama	Pan Pacific Copper 75%, Mitsui 25%	2014	Open-pit	SX-EW	30	SIC	113	14		(Consejominero.cl, 2015)
Cerro Colorado	Antofagasta	BHP Billiton (100%)	1994	Open-pit	SX-EW	100	SING	335	42	8.6	(ICSG, 2013)
Cerro Dominador	Atacama	Callejas Group	2004	Open-pit	SX-EW	14	SIC	53	7		(ICSG, 2013)
Cerro Negro		Workers cooperative	1944	Open-pit	Concentrates	5		17	2		(ICSG, 2013)
Cerro Negro		Workers cooperative	1944	Open-pit	SX-EW	6		20	3		(ICSG, 2013)
Chagres smelter	Valparaíso	Anglo American (50.1%), Joint Venture (29.5%), Mitsubishi Corporation (20.4%)		Smelter	Copper anodes	145	SIC	145	18		(Consejominero.cl, 2015)
Radomiro Tomic	Antofagasta	Codelco	1997	Open-pit	SX-EW	380	SING	1274	159		(Consejominero.cl, 2015)
Chuquicamata	Antofagasta	Codelco	1915	Open-pit/Smelter	Electrorefined cathodes/SX-EW/Concentrates	339	SING	1230	154	38.9	(Consejominero.cl, 2015)
Collahuasi	Tarapacá	Anglo American (44%), Glencore (44%), Mitsui + Nippon (12%)	1999	Open-pit	Concentrates	400	SING	1211	151		(ICSG, 2013) (Consejominero.cl, 2015)
Collahuasi	Tarapacá	Anglo American (44%), Glencore (44%), Mitsui + Nippon (12%)	1999	Open-pit	SX-EW	44	SING	148	18	3.8	(ICSG, 2013) (Consejominero.cl, 2015)
Dos Amigos	Atacama	CEMIN		Open-pit	SX-EW	10	SIC	38	5		(ICSG, 2013)
El Abra	Antofagasta	Codelco (49%), FreeportMcMoRan Copper & Gold Inc. (51%)	1996	Open-pit	SX-EW	156	SING	523	65	13.9	ICSG, 2013 (Consejominero.cl, 2015)

Appendix 1 Operating mines in Chile (2/3)

Mine	Region	Operator/Owner(s)	Start up	Mine type	Process	Production (thousand metric tons)	Electrical grid	Electricity demand (GWh/a)	Constant electricity demand (MW) (8000 h/a)	Heat demand, MW_{th}	Source
El Bronce de Atacama (Kozan)	Atacama	Nittetsu Mines (60%), Inversiones Errazuriz (40%)	2003	Open-pit	Concentrates	15	SIC	56	7		(ICSG, 2013)
El Soldado	Valparaíso	Anglo American (50.1%), Joint Venture (29.5%), Mitsubishi Corporation (20.4%)	1942	Open-pit	Concentrates	46	SIC	173	22		(ICSG, 2013) (Consejominero.cl, 2015)
El Soldado	Valparaíso	Venture (29.5%), Mitsubishi Corporation (20.4%)	1942	Open-pit	SX-EW	6	SIC	23	3		(ICSG, 2013) (Consejominero.cl, 2015)
El Teniente	O´Higgins	Codelco Chile	1906	Open-pit/underground	Concentrates	450	SIC	1898	237		(ICSG, 2013) (Consejominero.cl, 2015)
El Teniente	O´Higgins	Codelco Chile	1906	Open-pit	SX-EW	4	SIC	15	2		(ICSG, 2013)
El Tesoro (part of Centinela)	Antofagasta	Antofagasta Plc (70%), Marubeni Corporation (30%)	2001	Open-pit	SX-EW	100	SIC	376	47	17.6	(ICSG, 2013)
Escondida	Antofagasta	BHP Billiton (57.5%), Rio Tinto Corp. (30%), Japan Escondida (12.5%)	1990	Open-pit	Concentrates	900	SING	2725	341		(ICSG, 2013)
Escondida	Antofagasta	BHP Billiton (57.5%), Rio Tinto Corp. (30%), Japan Escondida (12.5%)	1990	Open-pit	SX-EW	350	SING	1174	147	9.8	(ICSG, 2013)
Esperanza (part of Centinela)	Antofagasta	Antofagasta Plc (70%), Marubeni Corporation (30%)	2010	Open-pit	Concentrates	191	SING	578	72		(ICSG, 2013)
Franke	Atacama	Quadra Mining Ltd	2009	Open-pit	SX-EW	30	SIC	101	13		(ICSG, 2013)
Gabriela Mistral (Gaby)	Antofagasta	Codelco	2008	Open-pit	SX-EW	128	SING	429	54		(ICSG, 2013) (Consejominero.cl, 2015)
La Cascada (Sagasca)	Tarapacá	Haldeman Mining Company	1972	Open-pit	SX-EW	19	SING	64	8		(ICSG, 2013)
Las Luces	Antofagasta	Cia. Minera Las Cenizas S.A	1996	Underground	Concentrates	9	SING	31	4		(ICSG, 2013)
Lomas Bayas	Antofagasta	Glencore	1998	Open-pit	SX-EW	74	SING	429	54	11.1	(ICSG, 2013) (Consejominero.cl, 2015)
Los Bronces	Metropolitana	Anglo American (50.1%), Joint Venture (29.5%), Mitsubishi Corporation (20.4%)	1925	Open-pit	Concentrates	378	SIC	1423	178		(ICSG, 2013) (Consejominero.cl, 2015)
Los Bronces	Metropolitana	Anglo American (50.1%), Joint Venture (29.5%), Mitsubishi Corporation (20.4%)	1925	Open-pit	SX-EW	50	SIC	168	21		
Los Pelambres	Coquimbo	Antofagasta Plc (60%), Nippon Mining (25%), Mitsubishi Materials (15%)	1992	Open-pit	Concentrates	405	SIC	1525	191		(ICSG, 2013) (Consejominero.cl, 2015)

Appendix 1 Operating mines in Chile (3/3)

Mine	Region	Operator/Owner(s)	Start up	Mine type	Process	Production (thousand metric tons)	Electrical grid	Electricity demand (GWh/a)	Constant electricity demand (MW) (8000 h/a)	Heat demand, MW_{th}	Source
Ministro Hales	Antofagasta	Codelco	2013	Open-pit	Concentrates	34	SING	103	13		(Codelco, 2014) (Consejominero.cl, 2015)
Mantos Blancos	Antofagasta	Anglo American	1961	Open-pit	Concentrates	40	SING	121	15		(ICSG, 2013) (Consejominero.cl, 2015)
Mantos Blancos	Antofagasta	Anglo American	1961	Open-pit	SX-EW	30	SING	101	13	10.2	(ICSG, 2013) (Consejominero.cl, 2015)
Mantos de la Luna	Antofagasta	Izquierdo Menendez Group	2006	Open-pit	SX-EW	24	SING	80	10		(ICSG, 2013)
Mantoverde	Antofagasta	Anglo American	1995	Open-pit	SX-EW	50	SIC	188	23	10.4	(ICSG, 2013) (Consejominero.cl, 2015)
Michilla	Antofagasta	Antofagasta Plc (74.2%), Grupo Cueto (17.8%), Others (8%)	1970	Open-pit/underground	SX-EW	38	SING	127	16	12.9	(ICSG, 2013) (Consejominero.cl, 2015)
Ojos del Salado	Atacama	Inc. (80%), Sumitomo Corp. (20%)	1970	Underground	Concentrates	23	SIC	87	11		(Consejominero.cl, 2015)
Punitaqui	Coquimbo	Glencore	2010	Underground	Concentrates	12	SIC	45	6		(Consejominero.cl, 2015)
Quebrada Blanca	Tarapacá	Inversiones Mineras SA 13.5%, Enami 10%	1994	Open pit	SX-EW	56	SING	188	23	5.4	(Teck, 2014)
Salvador	Atacama	Codelco	1927	Open-pit/underground	Electrorefined cathodes	40	SIC	216	27		(ICSG, 2013)
Salvador	Atacama	Codelco	1927	Open pit	SX-EW	14	SIC	53	7		(ICSG, 2013)
San Jose (Socavon)	Atacama	Sociedad Punta del Cobre (Pucobre)	1971	Open pit	Concentrates	30	SIC	101	13		(ICSG, 2013)
Spence	Antofagasta	BHP Billiton	2007	Open-pit	SX-EW	200	SING	671	84		(ICSG, 2013)
Tres Valles	Atacama	Vale	2010	Open-pit/underground	SX-EW	18	SIC	68	8		(ICSG, 2013)
Various small mines		ENAMI and Small Mine Owners		Open pit	Concentrates	96		329	41		(ICSG, 2013)
Various small mines		ENAMI and Small Mine Owners		Open pit	SX-EW	50		168	21		(ICSG, 2013)
Ventanas smelter	Valparaíso	Codelco	1964	Smelter	Electrorefined cathodes	400	SIC	636	79	35.1	(Codelco.com, 2015)
Zaldivar	Antofagasta	Barrick Gold Corp.	1995	Open pit	Concentrates	3	SING	9	1		(ICSG, 2013)
Zaldivar	Antofagasta	Barrick Gold Corp.	1995	Open pit	SX-EW	120	SING	402	50	8	(ICSG, 2013)

Appendix 2 Categorization of operating copper mines according to the electric power demand

Operating copper mines with a constant electric energy demand of 1 – 20 MW

Mine	Grid	Process	Production (ktCu)	Electrical power demand (MW)	Heat demand (MW)
Las Luces	SING	Concentrates	9	4	
Cerro Negro		SX-EW/conc.	11	5	
Dos Amigos	SIC	SX-EW	10	5	
Punitaqui	SIC	Concentrates	12	6	
Cerro Dominador	SIC	SX-EW	14	7	
El Bronce de Atacama (Kozan)	SIC	Concentrates	15	7	
Tres Valles	SIC	SX-EW	18	8	
La Cascada (Sagasca)	SING	SX-EW	19	8	
Mantos de la Luna	SING	SX-EW	24	10	
Ojos del Salado	SIC	Concentrates	23	11	12.9
Franke	SIC	SX-EW	30	13	
Ministro Hales	SING	Concentrates	34	13	
San Jose (Socavon)	SIC	Concentrates	30	13	
Michilla	SING	SX-EW	38	16	
Chagres smelter	SIC	Copper anodes	145	18	

Operating copper mines with a constant electric energy demand of 20 - 50 MW

Mine	Grid	Process	Production (ktCu)	Electrical power demand (MW)	Heat demand (MW)
Mantoverde	SIC	SX-EW	50	23	10.4
Quebrada Blanca	SING	SX-EW	56	23	5.4
El Soldado	SIC	SX-EW/conc.	52	25	
Mantos Blancos	SING	SX-EW/conc.	70	28	10.2
Salvador	SIC	Electrorefined cathodes/SX-EW	54	34	
Antucoya	SING	SX-EW	85	36	
Andacollo	SIC	SX-EW/conc.	81	38	
Cerro Colorado	SING	SX-EW	100	42	8.6
Altonorte	SING	Copper anodes	309	47	
El Tesoro (part of Centinela)	SIC	SX-EW	100	47	17.6

Operating copper mines with a constant electric energy demand of 50 - 120 MW

Mine	Grid	Process	Production (ktCu)	Electrical power demand (MW)	Heat demand (MW)
Zaldivar	SING	SX-EW/conc.	123	51	8
Gabriela Mistral (Gaby)	SING	SX-EW	128	54	
Lomas Bayas	SING	SX-EW	74	54	11.1
El Abra	SING	SX-EW	156	65	13.9
Esperanza (part of Centinela)	SING	Concentrates	191	72	
Candelaria	SIC	Concentrates	168	79	
Ventanas smelter	SIC	Electrorefined cathodes	400	79	35.1
Caserones	SIC	SX-EW/conc.	180	85	
Spence	SING	SX-EW	200	84	
Andina	SIC	Concentrates	237	119	

Operating copper mines with a constant electric energy demand of > 120 MW

Mine	Grid	Process	Production (ktCu)	Electrical power demand (MW)	Heat demand (MW)
Chuquicamata	SING	Electrorefined cathodes/SX-EW/Concentrates	339	154	38.9
Radomiro Tomic	SING	SX-EW	380	159	
Collahuasi	SING	SX-EW/conc.	444	169	3.8
Los Bronces	SIC	Concentrates	378	178	
Los Pelambres	SIC	Concentrates	438	199	
El Teniente	SIC	SX-EW/conc.	454	239	
Escondida	SING	SX-EW/conc.	1250	488	9.8

Appendix 3 Electric energy consumption for desalination and pumping of copper mines in Chile

Status	Region	Operator	Mine	Altitude (m/s)	Desalination capacity (l/s)	Electricity consumption desalination (MW)	Electricity consumption pumping (MW)	Electricity consumption total (MW)	Annual electricity consumption (GWh)
Operation	Atacama	Freeport	Candelaria	800	400	5.8	2.0	7.8	67.1
Operation	Antofagasta	Antofagasta Minerals	Michilla	800	75	1.1	0.4	1.5	12.6
Operation	Antofagasta	SLM Las Cenzias	Las cenzias Tal Tal	1000	9.3	0.1	0.1	0.2	1.7
Operation	Antofagasta	Antofagasta Minerals	Esperanza	2230	50	0.7	0.7	1.4	12.3
Operation	Antofagasta	BHP Billiton	Escondida	3050	525	7.6	10.1	17.6	152.2
Operation	Atacama	AngloAmerican	Mantoverde	900	120	1.7	0.7	2.4	20.8
Construction	Antofagasta	Minera Quadra Chile	Sierra Gorda	1630	63	0.9	0.6	1.6	13.4
Construction	Antofagasta	Antofagasta Minerals	Antucoya	1700	280	4.0	3.0	7.0	60.7
Feasibility	Atacama	SCM Santo Domingo	Santo Domingo	1100	275	4.0	1.9	5.9	50.6
Feasibility	Tarapacá	Teck	Quebrada Blanca phase II	4400	1300	18.7	35.9	54.6	472.0
Feasibility	Atacama	Relincho Copper	Relincho	2200	700	10.1	9.7	19.7	170.6
Pre-freasibility	Tarapacá	Dona Ines de Collahuasi	Collahuasi	4400	1500	21.6	41.4	63.0	544.6
Study	Antofagasta	Codelco	Radomiro Tomic phase II	3300	1950	28.1	40.4	68.5	591.7
RCA Approved	Antofagasta	BHP Billiton	Escondida	3050	2500	36.0	47.9	83.9	724.7
RCA Pending	Atacama	Goldcorp	El Morro	4000	700	10.1	17.6	27.7	239.0

Source: (Cochilco, 2013, 2014) (Table 6)

Appendix 4 Interview questions

1. What is your general view of the mining industry in Chile today?

2. What are the typical power demands for concentrate production and SXEW?

3. How stable is the electric power demand throughout the day? Are there energy spikes caused by some processes? If yes, how large are they compared to the stable load?

4. Are there any thermal power demands for both concentrate production and SXEW?

5. Are there heat demands for auxiliary processes or heating of buildings at high altitudes?

6. I have seen mine owners in Chile investing in solar thermo plants providing heat for electrolyte heating. Has exhaust gases from thermal power stations/reciprocating engines been considered as heat source for this process? (CHP solution)

7. Are oil burners normally used to heat the electrolyte in electrowinning?

8. Do mine owners prefer to buy power from the grid or build their own power station?

9. How do mine owners secure the availability of power?

10. Are mine owners interested in self-supply of power in order to secure the power supply for future operations?

11. Are power purchase agreements (PPA) an increasing trend in the mining industry to secure power supply?

12. Are there types of copper mines that would require self-supply of power more than others?

13. What is the community's view on LNG and HFO as fuel for power generation?