MSc Program
Environmental Technology & International Affairs

A Comparison of the Effects of Primary Copper Mining in Chile and Secondary Copper Mining in Austria and the Resulting CO2 Emissions and Economic Revenues

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, March 28, 2014

Affidavit

I, **LINA PISKERNIK**, hereby declare

1. that I am the sole author of the present Master's Thesis, "A COMPARISON OF PRIMARY COPPER MINING IN CHILE AND SECONDARY COPER MINING IN AUSTRIA AND THE RESULTING CO2 AND ECONOMIC REVENUES", 40 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

As the market price of copper is highly volatile, many countries have moved towards “urban mining” in order to reclaim secondary copper from infrastructure, electronics and other sources. The effects which this increased recycling of copper may have on the amounts of carbon dioxide emissions and profitability of the businesses are studied within this thesis. In order to study the economic effects of urban mining of copper, the manpower behind both secondary copper production and primary mining of copper was analysed as well as the profits of traditionally mine copper versus the secondary production option. The environmental aspect was analysed by exploring the carbon dioxide emissions of both opposing processes. It was found that the recycling of copper leads to reduced carbon dioxide emissions than the traditional copper mining in Chile. Urban mining was found to require less manpower than traditional copper mining, and is also the more profitable of the two processes.

Acknowledgements

I would like to take this opportunity to express my gratitude first and foremost to my supervisor Professor Paul H. Brunner, who was more than patient when providing me guidance in writing this thesis. Furthermore I would like to thank Ottokar Kramer and Professor Gerhard Sperl for providing their expertise so enthusiastically and on such a short notice. Lastly I would like to thank my father for his unwavering support of me.

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List of Abbreviations/Acronyms

Gg - gigagrams, which equal 1,000 metric tonnes

GHG - greenhouse gas

Mt - megatonnes, 1 mt = 1 million tonnes

MT- metric tonnen

MTF - metric tonne refined copper

SEC - Specific Energy Consumption

t Cu/a - tonnes per copper per year

USGS - United States Geological Survey

1. Introduction

Copper, a non-ferrous metal, has become a very important metal to the world economy due to its excellent ability to conduct electricity as well as its great repeated recyclability. In fact, copper can be recycled infinitely, which means that it does not lose its conductivity and physical qualities. This also means that the copper we may be handling on a daily basis, in coins for example, could contain copper from times as far back as ancient Egypt. (Copper Devlopment Association Inc., 2013)

Copper is predominantly used in transportation, such as cars in which a minimum of 25 kg of copper is to be found, trams and subways, for its electric conductivity, in electronic ware and appliances, as copper cable, and in buildings and construction. Copper also plays a very essential part in renewable energy since it is a necessity in wind turbines. Copper's conductivity is hard to be replaced, the closest being aluminium, of which much more is needed in order to replicate the conductivity. Silver and gold are also good conductors but are unfortunately too pricey. In the future, graphene might also become a viable option as a conductor.

As newly industrialized countries, like China, are growing at an increasing rate, more copper will be needed, while not many more reserves are being found. The world's largest copper mine, Escondida in Chile, has already peaked in 2007. The only mine that may be comparable to the Escondida is the Oyu Tolgoi mine in Mongolia, which is estimated to produce about half of its Chilean competitor in 2013. (The Economist, 2011)

Currently, copper prices are rising at a substantial rate, which leads to thievery in cities, where anything from copper roofs to copper air-conditioning parts are being stolen. There is also a lack of substitute for copper, which will lead to the copper prices staying high. Most alternatives for copper have already been used, such as using plastic piping by plumbers or aluminium heat exchangers for air conditioners. Copper is simply an irreplaceable metal and is a necessity for today's society.

1.1 Motivation

A large percentage of copper is mined in the country of Chile, which is in charge of most of the world's primary copper production. Chile is using advanced mining technology in order to acquire high quality copper to deliver to the world copper market. However, in recent years, the global ore-grade of copper has been declining due to the spike in mining production caused by the ever-increasing world demand. This has also been occurring in Chile, where, as of late, decreasing amount of copper is being mined, yet the amounts of energy used are increasing. Due to the amount of energy-use increasing, the amounts of carbon dioxide releases have been increasing as well.

The increased release of the greenhouse gas carbon dioxide, caused by mining, may impact only Chile on a short-term basis but will eventually impact the world climate, affecting every single country with the inevitable climate change that it induces. Therefore, it would be valuable to observe the effects that increased recycling of copper would have on the amounts of carbon dioxide released into the atmosphere.

Unlike other metals, copper can be recycled numerous times before losing only some of its conductive qualities. This can make the recycling of copper within a country with large amounts of copper stocks quite profitable, considering that less amount of primary copper would have to be purchased from producers and the country could become more self-reliant. Of course, the complete self-reliance on secondary copper will never be possible due to a certain amount of copper hibernating in permanent stocks in cities, which will either never be available for recycling or will only be available after an extended amount of time. Copper also irreversibly erodes when coming into contact with water, therefore having to be replaced by primary copper once again. This assures that a certain amount of primary copper will always be in need, regardless of the efficiency of copper recycling which can be attained, and that Chile will therefore always have a market in the world to sell its virgin copper to.

Austria is to be seen as an example of how a developed country within the European Union recycles copper. Like any developed country, Austria has large amounts of copper stocks and is in need of copper; and therefore can also profit from the re-use of copper in the future. As an environmentally conscious country, Austria also already greatly supports the act of recycling among its citizens as well as among its businesses while also having economically favourable climate towards the copper recycling industry.

1.2 Research Goals and Questions

Two aspects of copper recycling and primary production will be analysed in this thesis. First the primary production of copper in the Escondida mine in Chile will be considered. The revenues of copper produced per worker will be used as the economic indicator. This will be used as an indicator in order to show the value of the amount of copper being produced in each country. By being able to compare how much money is produced per worker in both Chile and Austria, one can see the most direct comparison monetarily. The environmental indicator for this study will be the amount of carbon dioxide produced by mining of virgin copper.

Second, we will consider the economic profitability of copper recycling for Austria. The economic criteria will be the monetary worth of the amount of copper produced per worker in the recycling process in Austria's only copper refinery, Brixlegg Montanwerke. The second aspect that will be considered is the ecological aspect of secondary copper production. In this case, the criteria used for analysing this aspect will be the carbon dioxide output of the recycling process.

There are three goals to this thesis, the first being that it will be analysed which process, primary mining or recycling of copper, is more beneficial to Austria. This will be followed of an analysis of which process would benefit Chile the most. Lastly, both processes will be analysed to observe which would benefit the environment the most.

1.3 Hypothesis

Copper recycling will be found to be the more environmentally friendly option when considering the global aspect, however, in Austria; more carbon dioxide will be emitted compared to simply buying the virgin copper on the market. It will be found that urban mining in will be found to be more profitable in than mining the copper in Chile. However, the Chilean environment would be released of many pollutants if copper mining was reduced, though this would be unfeasible for the current economy since about 20% of Chile's GDP consists of copper revenues and 60% of exports are related to copper. (The Economist a, 2013)

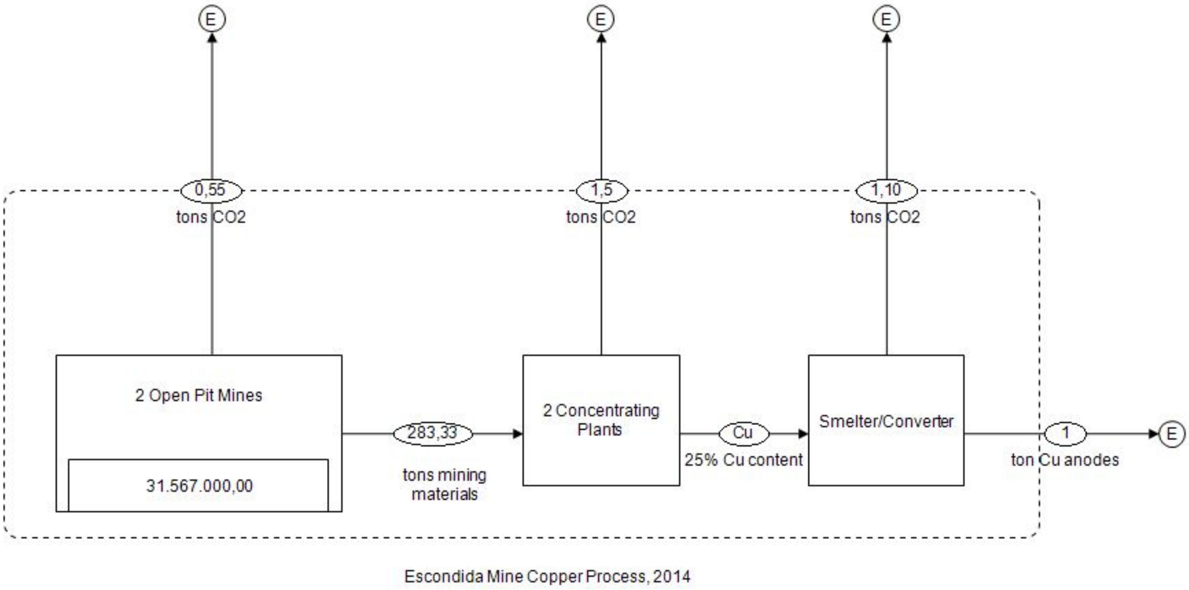
2. Methodology and Definitions

As mentioned before, the focus of this thesis will be on the carbon dioxide emissions and the monetary production of recycling and traditional primary copper mining. First, the emissions of carbon dioxide for every step of the primary and secondary copper production will be analysed. The economic aspects will be determined by comparing the amount of revenues created by the process of recycling a tonne of copper vs. the traditionally extracted copper from an open pit mine produces. The amount of employment that is needed recycling and extracting primary copper will also be considered. This will be done by determining the amount of copper that is produced at a facility, or mine, and then dividing this number by the supply of workers involved in the process. Therefore the tonne of copper per employee ratio can be found.

In order to be able to compare the two differing processes, a common end product had to be chosen. Copper recycling facilities as well as mines do not only produce pure copper cathodes, but also many other copper products. For example, the Escondida mine produces not only copper cathodes, but also copper anodes and copper concentrate. Meanwhile the Brixlegg Montanwerke produces copper cathodes and anodes along with by-products of the recycling process. It was decided that the common end product for both processes would be copper anodes. Any other products which Brixlegg or the Escondida mine would produce will therefore be converted, through calculation, back into copper anodes with a 99% copper content.

2.1. Definitions

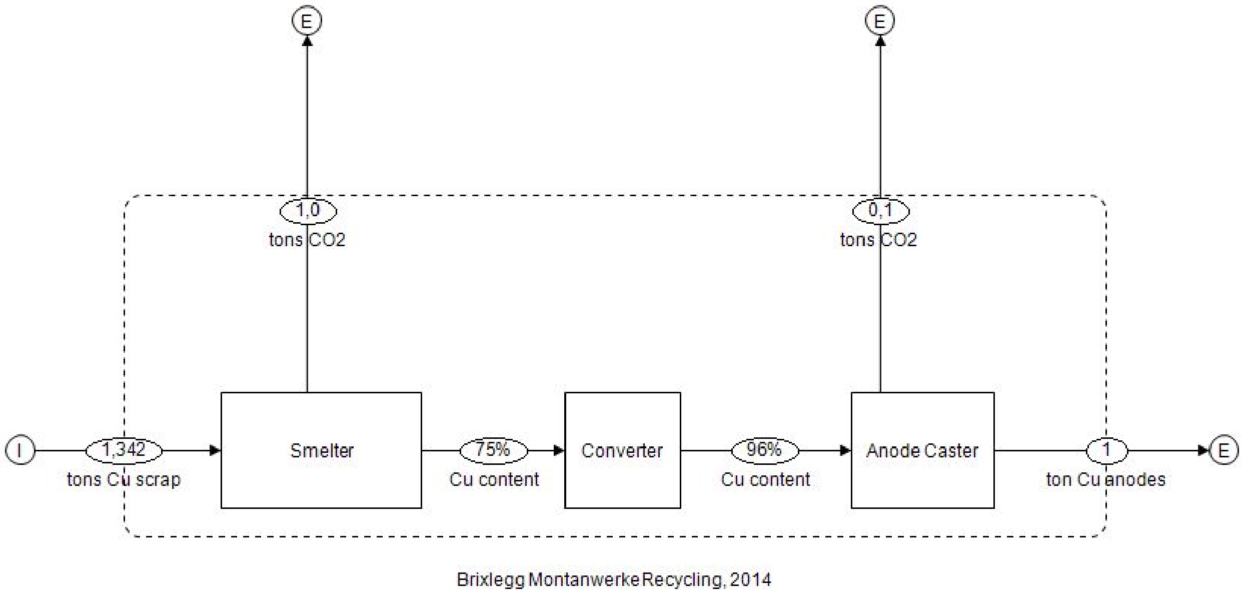
Escondida Mine Material Flow Analysis[1][2]



The material flow analysis for the Escondida Mine shows the amount of material needed in order to produce one tonne of copper anodes, while also showing the amount of carbond ioxide produced. This diagram does not show mass balances, but is instead an unbalanced flow diagram.

[1] (Chilean Copper Commission Resarch Policy and Planning Department, 2009)
[2] In order to make this Material Flow Analysis the methodology described in the Practical Handbook of Material Flow Analysis by P.H. Brunner and H. Rechberger was used.

Brixlegg Copper Refinery Material Flow Analysis[3][4]



The material flow analysis for Brixlegg shows the amount of copper scrap needed to produce one tonne of copper annodes and the amount of the resulting carbon dioxide emissions. This is not meant to show mass balances but instead show an unbalanced flow diagram.

[3] Emissions estimation sources: (Chilean Copper Commission Resarch Policy and Planning Department, 2009) (Oeggl, 2013)
[4] In order to make this Material Flow Analysis the methodology described in the Practical Handbook of Material Flow Analysis by P.H. Brunner and H. Rechberger was used.

3. Primary Copper Production in Chile

Chile currently has the largest estimated reserves of primary copper in the world, followed by China and Peru. Chile's production and reserves, however, greatly outweigh the two latter countries showing the dominance that Chile has over the world market in terms of resources.

Currently Chile is the biggest copper producer in the world, providing about 34% of global production. Meanwhile, the next highest ranked countries, USA, China and Peru, can only provide up to 7% each. (Staniewska, 2012)

Table 3: World Copper Mine Production and Reserves, 2012 (thousand metric tonnes Cu content)

	Mine Production[5]	Reserves
Chile	5,370	190,000
United States	1,150	39,000
Australia	970	86,000
Canada	530	10,000
China	1,500	30,000
Congo (Kinshasa)	580	20,000
Indonesia	430	28,000
Kazakhstan	420	7,000
Mexico	500	38,000
Peru	1,240	76,000
Poland	430	26,000
Russia	720	30,000
Zambia	675	20,000
Other countries	2,100	80,000
World total (rounded)	17,000	680,000

Source: USGS Mineral Commodity Summaries,"Copper", 2013.

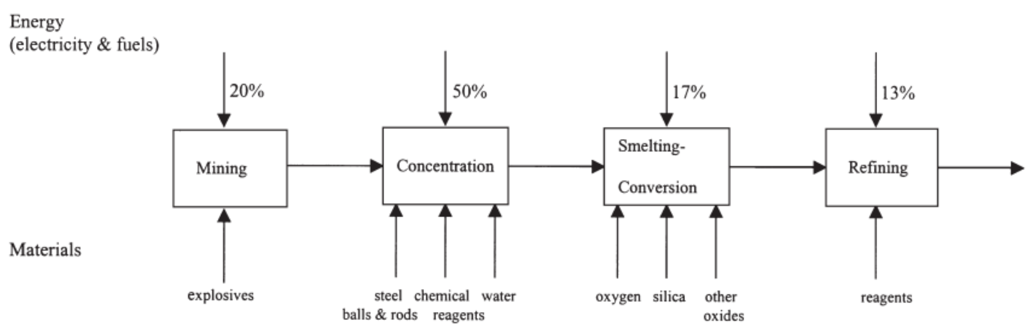
[5] Estimated by the USGS. (U.S. Geological Survey, 2013)

3.1 Copper Mining and Production Processes

In order to understand the amounts of carbon dioxide and energy used by the processes of copper mining, it is necessary to discuss the processes that are needed to create the copper that is a necessity in today's world. The pyrometallurgical processing route accounts for more than 85% of the copper production process, while the hydrometallurgical route accounts for about 15%. Therefore the focus will be on primary processing of copper in the form of pyrometallurgy. (Frischenschlager et al., 2010)

The pyrometallurgical process of mining and processing copper ore consists of four steps: mining, concentration, smelting/conversion, and refining. Copper anodes are generally cast after the conversion process, producing a copper product that has 99 percent purity. In order to produce copper cathodes, of 99,99 percent purity, the copper coming out of the converter must then go through electrorefining. Since the end product studied will be copper anodes, the last step of refining will not be considered.

Figure 3.1: Main external inputs for copper production. Energy is given as percentage of total SEC



Source: (Alvarado et al., 1999)

3.1.1 Copper Extraction through Mining

Two types of copper ore are to be found in the mining process, sulfide ore and oxide ore. Oxide ores are leached while sulfide ores are extracted through flotation cells.

To extract copper, through open-pit or underground mining, explosives are necessary in order to expose the copper ore. The copper ore is then loaded onto a truck to be transported to the primary crushers. The copper ore is then crushed and screened into fine sulfide ore and coarser ore.

3.1.2 Concentration of Copper and Smelting

The coarser ore is sent to a heap leach pad outside, where the copper ore is dissolved with a sulfuric acid solution. The heap leach is sprayed with a diluted sulfuric acid solution and the dissolved material flows to a pond at the bottom of the pad. The leach solution then undergoes the process of solvent extraction, during which a chemical reagent is added that binds to and extracts the copper. This makes the copper easily separable from the reagent. The separated copper is then sent to the smelter.

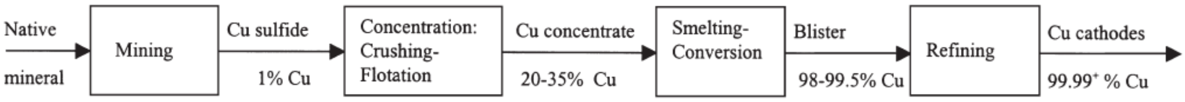
To recover the copper from the fine sulfide ore, it is sent to froth flotation cells, a process during which sulfide ores are attached to a chemical bubble, resulting in an overflowing froth which contains the copper. The resulting froth is then sent to the smelter. During the smelting process the copper won from the flotation cells is melted into a copper plate. (Copper Mining Info, 1994-2012)

3.1.3 Anode Casting

The dissolved copper leach solution, along with the separated concentrated copper from the solvent extraction process, is sent to the anode caster, which then plate the copper into anodes. These anodes are then sent into the industry to be manufactured into wiring, pipes, and other necessities for the modern age.

If copper cathodes are produced then the resulting copper from the smelting-conversion process would then be sent to electro refining to be further processed into the purest form of copper possible.

Figure 3.1.3: The Illustrated Copper Mining and Production Process



Source: (Alvarado et al., 1999)

3.2 Environmental Effects of the Production of Primary Copper

The negative effects which primary copper production has on the environment are widespread. Primary copper plants release emissions into the atmosphere and water while creating solid residues as well.

In certain processes, water contamination occurs during wet gas cleaning, slag granulation, hydrometallurgical treatment, electrolytic processes, cooling water and surface run-off. These waters maybe contaminated with suspended solids, heavy metals, sulphates and sulphites. The pH-value of the water is also put into compromise. Naturally, before being released into the environment, the water is treated at a treatment plant. However, there is still a danger of both water and soil contamination by accident.

During the process of creating primary copper, solid materials are also produced which come in the form of slags, precipitates, dusts, and sludges. The major parts of the by-products are generated into marketable products that are then sold.

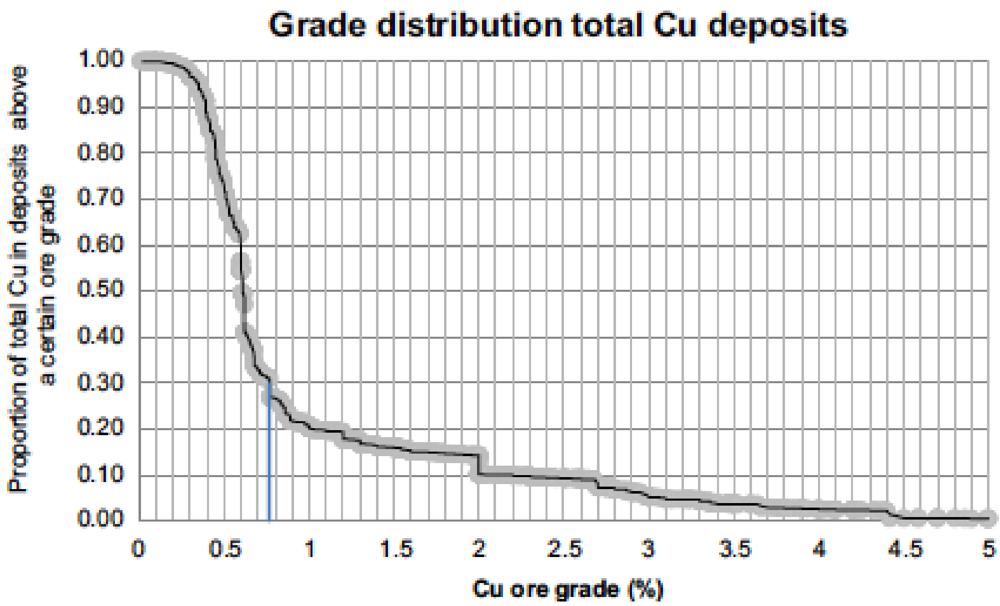
Emissions of contaminants into the atmosphere also occur during the primary copper process. During the mining, as well as during the concentration, smelting and refining processes, dust particles, metals and gases hazardous for the atmosphere are released.

The two most important atmospheric gases that are released during these processes are SO_2 and carbon dioxide. There has been a worrying increase in amounts of carbon dioxide released by the copper mining industry due to the increase of energy needed. Due to this development, the carbon dioxide emissions of primary copper production will be concentrated on in this paper.

3.2.1 Energy-Use

The copper industry in Chile, and the world, has become highly energy intensive due to the ore-grades diminishing over time. During the 17th and 18th century in England, ores consisted typically of 7 to 10% copper. Today, it would be uncommon to mine ore consisting of more than 1% copper. (Alvarado et al., 1999)

Figure 3.2.1:



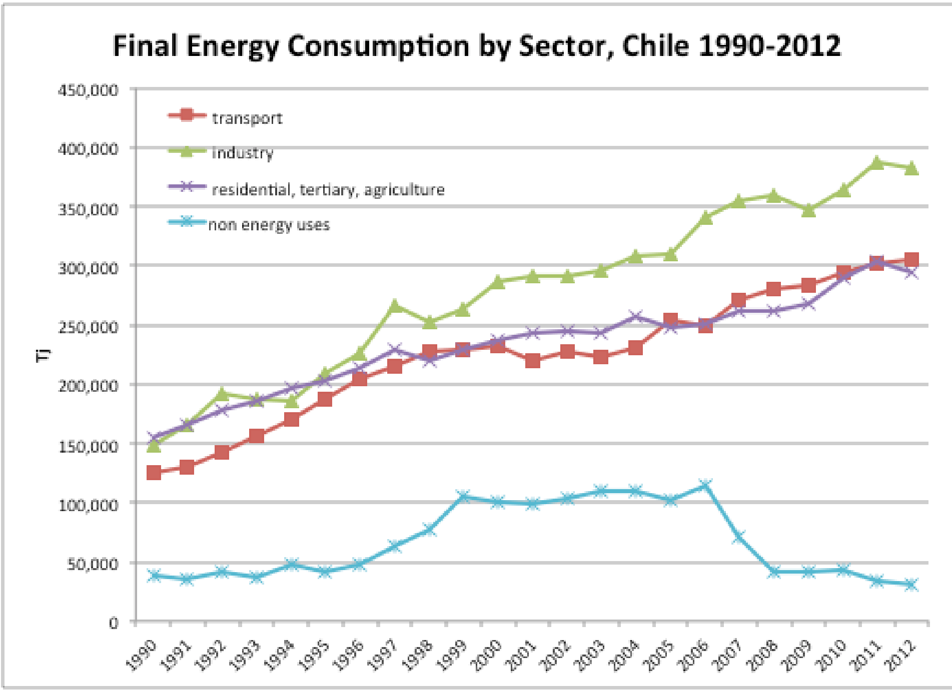
Source: (Harmsen et al., 2013)

Due to this increase in energy use needed in order to purify the copper, the amount of carbon dioxide released into atmosphere is also increasing drastically. Energy-use in the primary copper industry converges at the process of concentrating the metal. Typically, about 50% of the total energy used by the industry is employed in this process. Approximately 20% of operating costs are represented by energy and the Chilean copper mining industry account for 27% of oil-derived fuel and 38% electricity consumption. (Alvarado et al., 1999) The main sources of electricity in Chile are thermal and hydropower, with nearly 65% of total installed capacity being thermal power and 34% being hydroelectric. (Central

Energia , 2012) The amount of energy and fuel needed by the Chilean copper mining industry is also expected to increase in the future due to the increase in energy necessary for the lower ore grade copper to be obtained.

One of the most alarming developments of the past years is that the amount of copper produced has been falling while the total energy consumption has been rising. In 2008, the total Chilean copper production fell by 2 percent while the total estimated energy consumption rose by 21 percent. Sadly this is also a global trend, with the total global fuel consumption increasing by 12 percent in 2008. (Chilean Copper Commission Research and Policy Planning Department, 2009)

Figure 3.2.2:



Data Source: (Enerdata, 2013)

3.2.1.1 Chilean Energy Sources

Though Chile is seen as an economically successful South American country, it is poor when considering fuel sources. Chile imports 75% of its fuel needs in form of fossil fuels. Finding a reliable source of this energy has also been difficult, with Argentina recently backing out of a gas contract. Buying from Bolivia or Peru is not an option due to current border disputes between the three countries preventing trade. Liquefied natural gas (LNG) plants have been built, but are expensive to use.

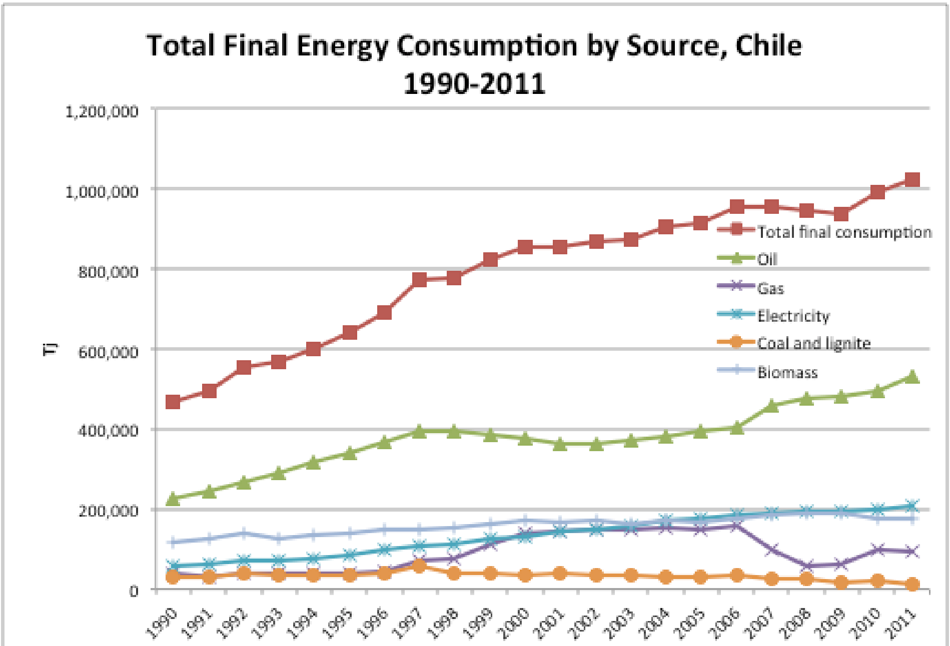
The idea of nuclear energy was also toyed with before the Fukushima disaster put this form of energy into a bad light. This has left Chile with the option of expanding its hydroelectricity sector. Currently, 40% of Chile’s energy is already provided by hydroelectric power, and plans have been made to build 5 more dams on two Patagonian waterways, which would provide 18,000 gigawatt-hours of electricity per year but would also lead to the flooding of 5,900 hectares of nature. However, environmentalists have been protesting this project. (G.L., 2012) The newly elected government has also taken a negative stance towards the project, leading it to be put on hold for now.

In order for Chile to develop further economically, more and more electricity will be needed. To assure Chile’s autonomy, new energy sources must come from within the country. Luckily, Chile’s vast and varying landscape has a great potential for several types of renewable energy sources. These sources range from solar power in its deserts, biomass and hydropower in its forests and rivers, geothermal energy from its volcanoes, tidal and wave power along its coastline and wind power from the powerful winds that sweep across the country. (von Hatzfeld, 2013)

The Chilean government has recognized its country’s need for energy and has therefore appointed the target of creating 10% of its electricity from renewable sources by 2020. This means that by 2010 about 5% of the nation’s energy needs would had to have been met with renewable energy sources, however, sadly, only 2% was reached.

Currently the future prospects of Chile’s energy sector seem to be dire, with hydroelectricity being one of the only local sources considered, yet the major resistance by environmentalist and the government are keeping any more development in this sector from occurring. The future of the energy supply will most likely be one of dependence on carbon-based fuels imported from neighboring countries

Figure 3.2.1.1:



Data Source: (Enerdata, 2013)

In the table below it can be seen how much potential Chilean renewable energy sources actually have while there is still a fair amount of capacity that can be installed.

Chile has a very high potential when it comes to renewable energy sources, however, it can be seen in the graph above that there is a higher energy demand than the renewable sources can provide Oil is still the energy source most consumed.

Figure 3.2.1.2: Current Installations and Construction of Renewable Energies

Renewable Energy Source	Small Hydraulic (<20 MW)	Wind	Biomass	Solar	Total
In Operation	278 MW	250 MW	394 MW	2.4 MW	880 MW
Under Construction	114 MW	107 MW	58 MW	2.5 MW	281 MW

Source: (Olivares and Maldonado, 2012)

3.2.2 Carbon Dioxide Emissions of the Chilean Copper Industry

Between 2004 and 2008 global GHG emissions due to copper production have increased by 48 percent, from 11.5 to 17 million tonnes of carbon dioxide per year. The increase in GHG emissions in Chile is believed to be due to a change in the energy mix of the grids providing the industry. Previously, natural gas and hydroelectricity provided a large amount of energy to the industry. In 2008, these sources were being replaced by coal, pet coke, thermal source and diesel. (Chilean Copper Commission Research and Policy Planning Department, 2009)

Figure 3.2.2: GHG emissions of the Chilean copper mining industry due to process fuel and electricity

GHG emissions due to process fuel (Gg)

Year	1994	2000	2005	2010	2015	2020
CO_2	1956.5	2344.7	2225.6	2489.4	2793.3	3143.4
SO_2	9.23	5.60	1.56	1.69	1.83	1.98
CO	5.58	10.21	10.90	12.26	13.82	15.62
CH_4	0.09	0.12	0.11	0.12	0.14	0.16
NO_x	17.27	29.34	27.19	31.58	36.61	42.37
COVNM	1.25	2.37	2.44	2.77	3.14	3.57
N_2O	0.03	0.05	0.05	0.05	0.06	0.07

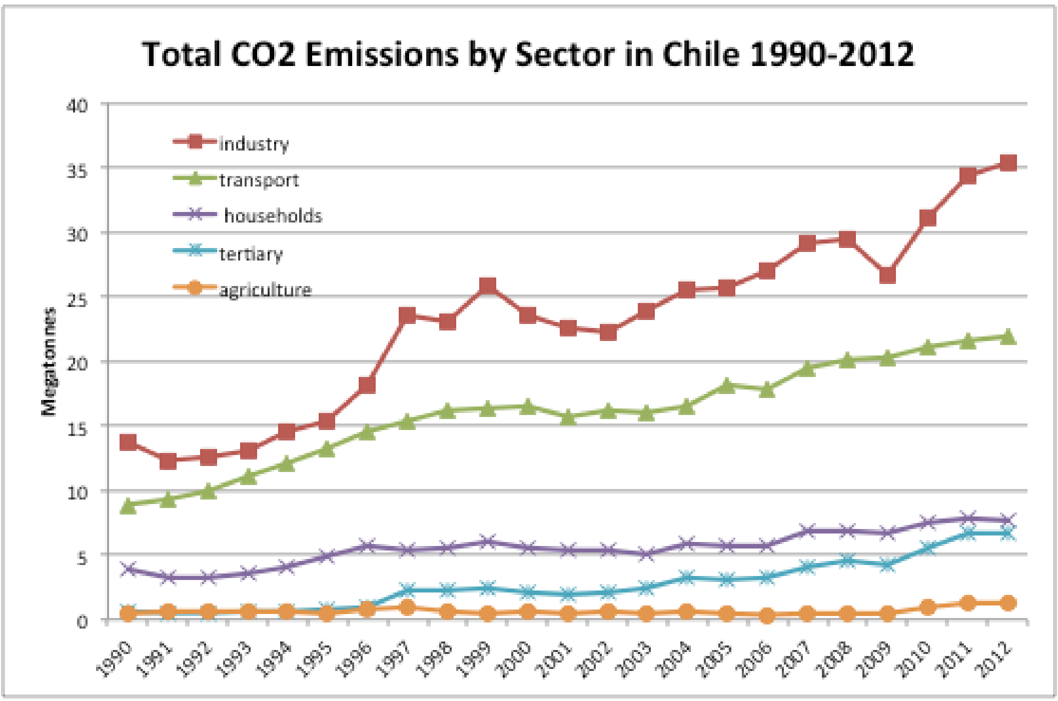
GHG emissions due to electricity (thermal power) consumption (Gg)

Year	1994	2000	2005	2010	2015	2020
CH_4	0.05	0.10	0.09	0.10	0.11	0.12
N_2O	0.05	0.04	0.01	0.01	0.01	0.01
NO_x	10.37	14.83	9.77	10.63	12.09	13.98
CO	0.70	1.49	1.36	1.49	1.69	1.94
COVNM	0.18	0.36	0.32	0.35	0.40	0.46
SO_2	7.49	3.21	0.03	0.04	0.04	0.04
CO_2	3308	5026	3659	3987	4529	5234

Source: (Alvarado et al., 2002)

At this time it seems that the carbon dioxide emissions will not be decreasing even though the Chilean government is currently attempting to encourage the installation of more renewable energy sources by setting the lofty goal of deriving 10% of the country's electricity from renewable sources by 2020.

Figure 3.2.3:



Data Source: (Enerdata, 2013)

3.2.2.1 Carbon Dioxide Emissions of the Escondida Mine

In order to be able to estimate the financial and environmental profitability of producing virgin copper in Chile, it was decided upon to use the Escondida mine in Antofagasto, Chile as an example. The Escondida mine is an open pit mine located in the Atacama Desert in the northern part of Chile. As of 2009, it is known to have a copper stock of 31,567 million tonnes of copper with the average copper grade being 2,12%. (InfoMine Inc., 2013) The mine is one of the largest in the world, being responsible for 2,5 % of Chile’s gross domestic product.[2] The Escondida mine consists of two open pit mines and two concentrator plants, which use sulfur flotation to concentrate the copper to a level of about 99% purity. From this point on copper anodes are produced with an anode caster. The mine produces 3,2 mt of copper concentrate and 330.000 tonnes of copper cathodes per year. Since the Escondida mine produces mostly copper concentrate, at an average amount of 30% content of copper, and copper cathodes, the purest form of copper at 99.99%, it was decided upon using copper anodes as a common denominator. The use of copper anodes as the common denominator also will help further analysis with easing the comparability of the recycling process in Brixlegg Montanwerke to the virgin copper process of the Escondida Mine.

The overall carbon dioxide emissions of virgin copper mines have been broken down into the processes that emit the gas.

Figure 3.2.2.1:

Unit Emission Loads by Process Area

	Unit	2004	2005	2006	2007	2008
Open Pit	MT CO2 eq. /MTF ore	0.38	0.42	0.44	0.47	0.55
Underground	MT CO2 eq. /MTF ore	0.17	0.20	0.22	0.31	0.28
Concentrating Plant	MT CO2 eq. /MTF concentrate	0.92	0.92	1.04	1.40	1.50
Smelter	MT CO2 eq. /MTF anodes	0.84	0.81	0.86	1.08	1.10
Refinery	MT CO2 eq. /MTF ER cathodes	0.24	0.25	0.22	0.30	0.30
LX-SX-EW	MT CO2 eq. /MTF EW cathodes	2.06	1.92	2.21	2.67	2.81
Services	MT CO2 eq. /MTF total production	0.10	0.10	0.10	0.11	0.17

Source: (Chilean Copper Commission Research and Policy Planning Department, 2009)

For the analysis of the total carbon dioxide amount produced by the Escondida mine per tonne of anode copper, the refinery, the LX-SX-EW manufacturing process, and Services were left out. The most recent values from 2008 were used. The process of producing copper anodes ends after the smelter, when the anodes are cast. Also, the Escondida mine does not have an underground mine, therefore this value was not used.

The results showed that per 1 tonne of copper anodes produced, 3,1 tonnes of carbon dioxide were produced. With an annual production of 1.303.333 tonnes of copper anodes, the Escondida mine produces about 4.040.322 tonnes of carbon dioxide annually.

3.3 The Economics of Primary Copper Mining

Figure 3.3: The Estimation of Profitability per Copper Miner per Year in the Escondida Mine in Antofagasto, Chile

Est. Amt. Copper Workers in Mine[6]	Tonnes of Raw Materials Mined per Year[2]	Tonnes of Copper Anodes Produced per Year[7]	Price of Copper Anode per Tonne[8]	Tonnes of Anodes per Miner Per Year Produced[9]	$ of Copper Mined per Workers per Year[10]
203.000	370.000.00	1.303.333	$7.074,10	6,42	$45.415,72

The Escondida mine is one of the most profitable in the world, with approximately 203.000 workers producing 1.303.333 tonnes of copper anodes annually. This means that each worker produces approximately $45.423 a year at the copper price of $7.074,85 per tonne.

3.3.1 Carbon Tax

The concept of emission trading is not foreign to Chile. In the capital city of Santiago, emission trading was used in the late 1980s and early 1990s in order to curb the heavy pollution of the area. Environmentally the program was considered a success, with a reduction of emissions by 50% having occurred by 1998. However, the program was also hit by plenty of criticism by some academics, industry groups and government officials who claimed that too many obstacles were placed in the way of trade. (Schreifels, 2008)

Currently there is no national carbon trading market or carbon tax in place for the area in which the Escondida mine is located. This is an advantage for the

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[6] (InfoMine Inc., 2013)
[7] This number was found by taking the amount of copper concentrate and cathodes produced in the mine per year (according to infomine.com) and calculating into how many tonnes of copper anodes would be produced from these materials.
[8] (Montanwerke Brixlegg AG, 2014)
[9] This is the result of tonnes of anodes produced per year being divided by the amount of workers.
[10] This number was found by multiplying the tonnes of anodes produced per miner per year by the price of copper per tonne.

primary copper industry in Chile, since profitability is not in danger due to taxes based on amounts of carbon dioxide being released. Considering the amounts of carbon dioxide released by the industry, an emissions tax or trading scheme could have a significant impact on the profitability of the copper being produced. Even without a tax, producing primary copper is incredibly expensive, with several companies having invested a total of $4 billion by 2005. (InfoMine Inc., 2013)

3.4 The Economic Dependence of Chile on Copper

Since the discovery of copper in the mountains and the Atacama Desert of Chile, this essential non-ferrous metal has become a staple in the country's exports. Mines are spread throughout the country, ranging in all sizes. Small and medium-scale mines are required to work underground only, while large-scale mines are also allowed to operate open-pit mines.

Along with the numerous miners being employed by Chile's large-scale copper mines are many independet miners, called "pirquineros", who independently search for copper-rich rocks and sell their findings to the mines. (Staniewska, 2012)

A view of the correlation of copper prices and Chile's GDP (The Economist, 2013)

Chile's prosperity, or dearth, is mainly dependant on the variability of the copper market's prices. This has proven to be a problem in the past, when copper prices could drop suddenly, leaving Chile grappling for support.

Currently a Copper Stabilization Fund has been set up which gives Chile a bit of a leeway in case of a sudden drop of copper prices. The Copper Stabilization Fund is subsidized by the industry itself when prices are above the average global copper price rate. This extra money is then placed into the fund to be used later when the prices have declined below the average.

Copper mining alone accounted for 5.5% of Chile’s GDP in 2010. Today, copper is still Chile’s most important export, providing about one third of the world’s copper supply. (Eurostat, 2011)

4. Secondary Copper Production in Austria

Austria has a long history of metal mining and refining. In the Austrian state of Tyrol copper and silver was mined, and then sent to the town of Brixlegg, Tyrol, where the tradition of copper and silver refinery can be traced back to 1463. At the beginning of the 20th century, the copper supply was severely diminished, therefore leading to the Brixlegg refinery changing from primary to secondary processing. From then on copper was extracted from high-grade scrap metal alloys. (Punz and Müller-Thurau, 2012) Clearly the tradition of copper production in Austria is still alive and well today in the form of recycling. Brixlegg Montanwerke is currently the only copper refinery in Austria and therefore the only copper producer.

4.1 Copper Consumption in Austria

Austria's copper demand is estimated to be 340,000 t Cu/a, which is mostly covered by secondary copper already. About 305,000 t Cu of secondary copper is imported, processed within the country and then 223,000 t are exported once again. Therefore 80,000 tonnes of copper remains in Austria annually. The anthropogenic copper stock in Austria amounts to 1,400,000 t Cu with up to 80% of this stock being in buildings and infrastructure while the other 20% is present in durable consumer goods. The copper stock is still growing with 6-8% of more copper residing in Austria annually. (Daxbeck et al., 2006)

A view of the Brixlegg Montanwerke (Schrottkompass, 2013)

4.2 The Current State of Copper Recycling in Austria

The dominant provider of copper in Austria is the secondary copper industry. This means that nearly all of Austria’s copper demand is, in fact, supplied by previously recycled copper. Austrians are also extremely vigilant at recycling copper, with 90% of copper that ends up in waste management being recycled either within the country or abroad. The leftover 10% is landfilled and therefore will most likely never be recycled. (Daxbeck et al., 2006)

Brixlegg Montanwerke is the only secondary copper refinery in Austria, which is why it was chosen as a point of comparison for the Escondida mine. This refinery receives 160.000 tonnes of copper scrap each year and produces an output of 118.000 tonnes of the purest form of copper cathodes with a content of 99,99 percent. (Punz and Müller-Thurau, 2012)For comparison purposes, the amount of copper cathodes produced was converted to anodes, making the production rate of Brixlegg Montanwerke 119.200 copper anodes annually. Besides copper, precious metals such as gold, silver and platinum are also won as a result of the copper refinery process. By-products of the process, such as granos that are used in sandblasting or Flowbrix, which is used as a plant protection agent, are also sold to other industries. (Punz and Müller-Thurau, 2012) It is essential to Brixlegg Montanwerke that as few emissions as possible are produced by the refinery

process.

An example of typical copper scraps transported to Brixlegg for recycling (Montanwerke Brixlegg AG, 2014)

4.3 Copper Recycling Processes

Recently a new term for recycling of metals has come in use: urban mining. With the large amounts of copper invested in a city's infrastructure, copper is simply waiting to be "mined" again in order to be recycled. This form of mining is, naturally, not as energy intensive as conventional mining of copper, and is, in fact, far more environmentally friendly. In the following chapters, one will see the process involved in recycling one of the most important metals in the world once it has been "mined" and transported to Brixlegg.

4.3.1 Logistics

Before actually arriving to the copper smelting facilities, this valuable non-ferrous metal must first be "mined." The term "urban mining" would be appropriate for this procedure, considering the large amounts of copper "deposits" that can be found in the infrastructure and electronics of the world's cities.

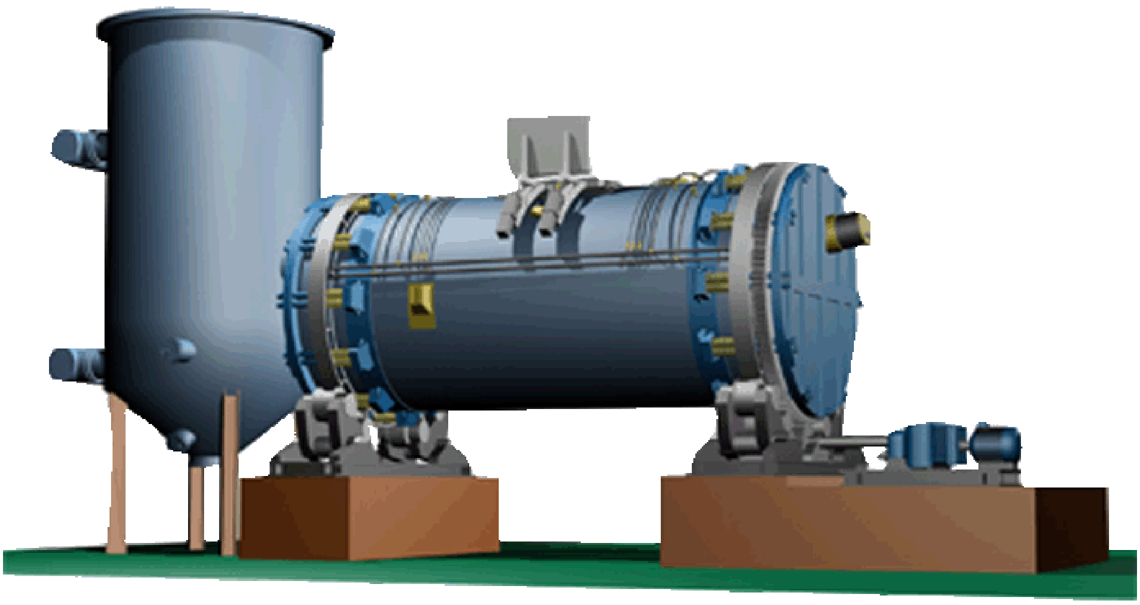
Scrap metal merchants and recycling facilities accumulate copper scraps and wastes in order to send them to the smelter facilities. Merchants and recycling facilities must usually sort through the scraps they receive in order to make it acceptable for a smelter. For example, in electric wiring, the metal must be separated from the insulation in order for the copper to be suitable for the smelter. This first form of processing of copper has a financial incentive since it adds value to the metal.

There is an internationally accepted standard for copper scraps, in order to make the process of copper recycling more accessible and also to protect public health. A long list of potentially hazardous chemicals and noxious materials, and the maximum amount of concentration of which can be contained in the copper scraps, exists in order to prevent any kind of harm to the public. For example, copper scraps may only contain certain amounts of arsenic, chlorine and mercury before they are seen as too toxic and therefore unrecyclable. (OECD, 1995)

4.3.2 Processing in the Copper Smelter and Refining

The process of smelting is carried on in both the conventional mining process as well as recycling process. In both instances it is also used to improve the grade of the copper. When the copper arrives at the refining facility it is first sent to the smelter where a blast furnace is used in order to raise the copper content from between 15% to 60% to circa 75% copper content.

Then it is sent to a converter or reverberatory furnace where the copper concentration is raised from 80% to 95%. It should be noted that the converter does not release any carbon dioxide because it runs simply on electricity; and since Brixlegg's energy mix consists of hydropower, no carbon dioxide emissions are created.



An example of an anode furnace (Kopar, 2010)

After the conversion process, the copper is sent to the anode furnace where further heating of the product leads to the copper product containing about 99% copper. The finished product of the anode furnace is then melted into anodes in the form which is most desired by the customer purchasing the copper. Besides anodes, there are also several other products which Brixlegg produces, such as copper cathodes and copper oxychloride.

The fumes and dust that result from copper recycling are collected with filters and are then returned to the blast furnace. The cleaned air is released into the atmosphere via chimney. The fumes that are collected contain high concentrations of metals, for instance, lead, tin and zinc, which can then be processed to produce the respective metals. The slags created from the process can either be recycled within the refinery or turned into products, which can eventually be sold on the market. (OECD, 1995)

4.4 Environmental Effects of Copper Recycling

It is common knowledge that recycling in general is viewed as the more environmentally friendly option compared to primary mining. Mainly this is due to the significant decrease in visible pollution. For instance, in primary copper mining large amounts of earth are moved, often with explosives. Meanwhile, in copper recycling, the only physical result is a relatively harmless slag, which the refineries often sell to companies for paving and construction. Energy-use and carbon dioxide emissions due to copper recycling are environmental effects, which are not visible to the eye but are still incredibly important to the environment as well as to the economy. Carbon dioxide emissions are also of economic importance due to Austria's participation in the carbon dioxide market of the European Union, put in place in order to adhere to the Kyoto Protocol.

Since Austria's only copper refinery is the Brixlegg Copper Refinery in Brixlegg, Tyrol, the following information is taken entirely from the refinery's 2012 Environmental Report.

4.4.1. Energy-Use

The yearly energy consumption of Brixlegg is 77,000,000 KWh. The most energy intensive process in secondary copper mining is electrolysis, which transforms copper anodes, of 99% purity, into copper cathodes, of 99.99% purity. Brixlegg disposes of three small hydroelectric power stations (Alpbach, Reith and Alpsteg), which produce about 25% of the needed electricity. The rest of the energy demand is provided by the powerplant TIWAG, which is also entirely hydroelectric power. (Punz and Müller-Thurau, 2012)This essentially means that no carbon dioxide is emitted due to energy use in Brixlegg. However, in order for the smelter and anode caster to obtain the heat needed, carbon fuels must be used, therefore leading to carbon dioxide emission inevitably.

4.4.2 Carbon Dioxide Emissions

Per one tonne of copper anodes produced, approximately 1,1 tonnes of carbon dioxide are released into the atmosphere. Since Brixlegg's power needs are provided for by hydroelectricity, carbon dioxide emissions due to processes in the converter are avoided entirely. The smelter produces the most carbon dioxide, with one tonne being produced per tonne of copper anodes produced. A large amount of energy is needed in the smelter, considering that items with the copper content of 30% are thrown into the smelter, producing a mass with a copper content of 75% before it is sent to the converter.

Meanwhile the converter runs purely on electricity, hydroelectricity in the case of Brixlegg, therefore producing no carbon dioxide. In the last step of the process, the anode caster, only 100 kilograms, or 0,1 tonnes, of carbon dioxide are produced. It should also be noted that copper scraps can have a copper content varying from 15 to 99%. The copper scraps with lower copper content are exposed to the entire secondary copper process, going through the smelter to the concentrator to the anode caster. However, copper scrap with higher copper content, such as copper cords, rails, or lamellar structures, will go directly into the anode caster, since intensifying the concentration of these substances is not necessary. Therefore less carbon dioxide will be produced when these products are recycled. It should be noted that sludge will also be returned from the anode caster to the concentrator and from the concentrator to the smelter, in order to ensure that the most copper content can be extracted from the process.

4.5 Carbon Tax

Austria participates in the European Carbon Dioxide Trade Market, which therefore means that Brixlegg has to pay a certain amount for its carbon dioxide emissions. In the table below, one can see the amount one year worth of carbon dioxide emissions would cost the Brixlegg Montanwerke. As of February 6th, 2014, the price of one tonne of carbon dioxide emissions in the European carbon dioxide market is € 6,60 or $9,12. However, according to analysts this price is still below the €25 threshold, which would actually affect business decisions. (Reed, 2014)Therefore the emissions trade in Europe is currently not as effective as was originally planned. With carbon dioxide emissions not being as large a monetary burden as originally planned, businesses are more lax on their emissions.

Figure 4.5: Estimation of the Monetary Burden of Carbon Dioxide Taxes on the Brixlegg Montanwerke

Tax Burdens due to Carbon Dioxide Trade per Tonne of Copper Anodes Produced[11]	Amount Potentially Paid per Year due to Carbon Dioxide Emissions
$22,03	$2.888.573

The above table shows the amount Brixlegg would be charged in the European carbon trading market. The amount of carbon dioxide emitted per year was multiplied by the cost of one tonne of carbon dioxide in the European carbon trading market.

In the case of Brixlegg, the amounts of emissions are so minimal that the carbon dioxide tax due to emissions trading does not seem to be disastrous for the refinery's business. Especially with the profitability of copper, the price of €6,60 per tonne of carbon dioxide will not make a dent in the prosperity of the copper refinery.

If this tax was levied upon the primary copper industry of Chile, however, a, effect would definitely be felt in the copper market of the world. Since much more resources and investment are needed in the case of primary copper mining, the production efficiency would certainly be affected.

4.6 The Economics of Secondary Copper Mining

The estimation of the profitability of secondary mining was determined by dividing the amount of anodes produced per year by the amount of workers in Brixlegg Montanwerke. The resulting amount was then multiplied by the price of copper per tonne. This determined amount then showed how much a Brixlegg copper worker produces monetarily in a year.

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[11] (Reed, 2014)

Figure 4.6: The Estimation of Profitability per Copper Worker per Year in the Brixlegg Montanwerke in Brixlegg, Austria

Amount of secondary copper workers in Brixlegg[12]	Tonnes of anodes produced per year[13]	Price of copper per tonne[14]	Tonnes per worker per year[15]	$ of copper per "miner" per year[16]
280	119,200 t	$7,074.10	425,71	$3.011.515,11

With 280 workers, Brixlegg Montanwerke is comparably smaller than the typical primary copper mine. However, in a monetary comparison of the Escondida mine and Brixlegg, one can see that Brixlegg workers produce monetarily far more than a primary mine worker. Working in a primary mine is, of course, more labour intensive and needs a much larger amount of workers and machinery than a refinery. The amount of energy and water needed by a primary mine should also not be forgotten when considering the two models of monetary estimations.

[12] According to (Montanwerke Brixlegg AG, 2014)
[13] This number was found by calculating the number of copper cathodes Brixlegg produces per year into anodes.
[14] Source: (Montanwerke Brixlegg AG, 2014)
[15] This number was found by dividing the amount of workers by the tonnes of anodes produced per year.
[16] This number was found by multiplying the amount produced per worker by the price of copper per tonne.

5. Results of comparing primary and secondary copper production

5.1 Chile

The primary copper industry in Chile is the most important industry of the country. Naturally, the government has taken precautions in order to protect the profitability of this industry. The lack of a carbon tax ensures that investment from companies outside of Chile is encouraged while still making a large profit from this precious metal. Without a carbon tax, there is also no pressure on the industry to stop using carbon-based fuels, resulting in higher carbon dioxide emissions.

5.1.1 Profitability

With a current lack of a carbon tax, as well as a politically favourable environment for now, the country and its copper businesses will continue to prosper. Chile’s copper mines continue to be heavily invested in, with the Escondida mine alone having an investment of about $4 billion and producing 3,2 megatonnes of copper concentrate and 333.000 tonnes of copper cathodes per year. (mineinfo.com) When calculating these amounts into copper anodes, the resulting amount produced per year is 1.303.333 tonnes, with one miner producing $45.423 per year.

As the grade of the copper continues to diminish more power will be needed in order to extract copper viable for the markets of the world. It has already been observed that a rise in energy use has been occurring within the copper industry. This naturally leads to a larger amount of money flowing into the use of power. Since it is predicted that power costs will further increase within Chile, the cost of producing copper will increase as well. (Fuentes, 2013)

It has also been predicted that the industry will be challenged with water scarcity within the next years. (Business Monitor, 2014) This is especially relevant for Chile, considering that the Escondida mine, the most profitable mine in the country, is located in the arid Atacama Desert in the north. Water is needed in all processes of mining and is therefore a most valuable commodity for the operation.

As the need for more power and water increases, but the local availability of these two precious commodities remains the same, with no further expansion of energy sources, the cost of mining copper in Chile will rise. With no current tax on carbon dioxide, the copper industry is still profitable and has an attractive investment environment.

5.1.2 Environment

Mining is widely known to be an environmentally degrading process. In the case of the Escondida mine, the numbers speak for themselves. In order to produce one tonne of copper anodes, 5,2 tonnes of carbon dioxide are produced, while 283,33 tonnes of mining materials are moved.

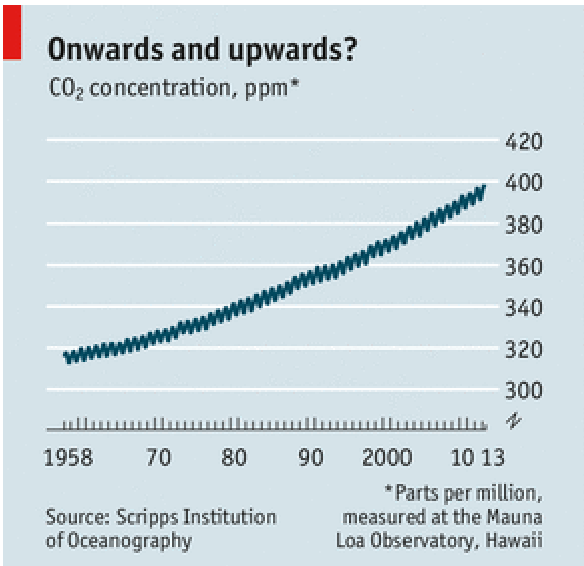
Regardless of current uncertainty in the Chilean copper industry due to a newly elected government, Chile is still predicted to have mined over 5,7M tonnes of copper in 2013, equating to almost 32% of the total copper mined in the world that year. (Business Monitor, 2014) With only one tonne of copper anodes, of 99% purity, producing 5,2 tonnes of carbon dioxide, it is hard to fathom the effects of the amounts of this greenhouse gas released into the environment in 2013 alone. However, the newly elected government of Michele Bachelet is predicted to make vast changes in forms of tax reform affecting the copper industry in the future, such as increasing the corporate taxes and making it more difficult for foreign companies to have access to Chilean markets. (Fuentes, 2013)

5.2 Austria

When discussing both profitability and environmental effects of secondary copper production, Austria seems to be lucky for Brixlegg Montanwerke switching from primary copper production to secondary at the beginning of the 20th century.

5.2.1 Profitability

Since Austria is part of the European carbon dioxide market, a tax is levied on every tonne of carbon dioxide produced. This tax was created in order to make the business responsible for the amount of carbon dioxide that it releases into the environment. According to analysts it wouldn’t effectively change business practices until one tonne of carbon dioxide costs €25 ($34,56). As of February 6th of 2014, a tonne of carbon dioxide costs €6,60 ($9,12). (Reed, 2014) With the current carbon dioxide output of 2,458 tonnes per 1 tonne of copper anodes produced, Brixlegg has to pay $22,03 per tonne of copper anodes produced. With 119,200 tonnes of copper anodes being produced per year, resulting in copper anodes valued at $8.5, a tax of $2.9 seems to be a measly sum. Especially considering that this carbon tax only amounts to about 0,03% of the value of copper produced annually at Brixlegg. However, in essence, this tax could potentially deter a business, which is, in the end, helping the environment as a whole by emitting the least amount of carbon dioxide possible while producing large amounts of a valuable metal that is very much in demand by developing and developed countries alike.



The rise of Carbon Dioxide Concentration in the atmosphere (The Economist b, 2013)

5.2.2 Environment

It is clear that the environment as a whole would prosper if copper recycling became more widespread than mining. Carbon dioxide outputs would be far lower, as can be seen in comparing the 1,1 tonnes of carbon dioxide produced in secondary copper production versus the 5,2 tonnes produced during primary copper production. However, it must be acknowledged that there is still carbon dioxide being released into the environment. No matter how little the amount of this greenhouse gas is released, it still supports global warming in the end. If Austria decided to stop producing secondary copper and would instead simply buy virgin copper from Chile, 131.120 tonnes of carbon dioxide would no longer be released into the atmosphere in the within the country. Naturally, production would therefore shift to Chile instead, where the carbon dioxide emissions would be shifted to as well. This would be a short-term solution for any country that would try to rid itself of carbon dioxide emissions, considering that the gas affects the climate globally eventually. The rise in carbon dioxide emissions has been proven to lead to a rise in the global temperature, leading to a permanent change in the global climate. In order for the temperature to rise no more than 2 degrees, the total carbon emissions would have to be drastically reduced immediately and then be cut completely to zero by 2017. (The Economist b, 2013)

6. The Future Prospects

6.1 Primary Copper Production

Regardless of recycling efficiency across the world, primary copper will always be a necessity in the global economy. In certain processes, such as erosion, copper is completely lost to the environment and therefore it will not be possible to recover completely.

A significant factor leading to an increasing need of primary copper is the incredible increase of demand originating from China. In fact, demand for copper in China increased by 6,5% in the first 11 months of 2013, compared to the same time period in 2012. This actually led to a production deficit of copper by 129.000 tonnes in 2013. (ISGS, 2014)

It should be noted that as the ore-grade of the copper inevitably declines, the amount of energy necessary in order to extract the copper increases. With future prospects of the power mix increasingly forming a dependence to carbon fuel imports from neighboring countries of Chile, a rise in carbon dioxide emissions will be a certainty for the country. (Fuentes, 2013)

A recent change in the political spectrum may also put pressure on the Chilean copper industry in the future. The election of Michelle Bachelet may lead to change in the industry as tax reforms will be reviewed by her advisors. There is some speculation that corporate tax rates may be increased from 20% to 25%. The potential nationalisation of water companies has also been speculated, which could lead to a significant impact on the water-intensive mining industry. Bachelet's new government has also opposed a 2,7 GW hydroelectric project, instead focusing on natural gas. Chile's energy prices are predicted to rise regardless of the several potential power mixes of the future and will most likely lead to an increase in imports of carbon-based fuels. (Fuentes, 2013)

6.2 Secondary Copper Production

Secondary copper production will become more relevant as the grade of copper declines even more over time. As global warming is becoming a more pertinent issue in today's world and the connection of carbon dioxide with global warming is becoming more obvious, secondary copper production will become even more applicable in society. Since secondary production releases significantly less carbon dioxide than primary production, recycling will become even more relevant in Austria, as well as in most other climate conscious countries across the globe. In 2014, the average newly made copper wire will contain about 30% recycled copper. (The Business of Mining, 2012)

For each tonne of copper anodes produced through recycling, rather than through primary mining, 4,1 tonnes of carbon dioxide emissions into the atmosphere are spared. This is an amount of about 78% of the primary copper emissions. The fact that recycling is also cheaper, by needing significantly less energy and resources, and more profitable, also makes an important case for the future of recycling copper. Although it seems that the benefits and profitability of recycling has not been a secret for quite some time, in 2010 2,25 million tonnes of copper were recycled, which was a 14 percent increase compared to 2009. (Deutsches Kupferinstitut Berufsverband, 2012)

7. Conclusion

Recycling copper will be a necessity in a future with decreasing copper grades and energy prices. As carbon dioxide emissions will only increase with the amount of primary copper being produced, recycling will be the most environmentally viable form of copper production. The mining process releases about 78% more carbon dioxide than the recycling process, making recycling the obvious choice for countries that need copper but are also environmentally conscious. Since copper can be recycled numerous times without it losing its qualities, the recycling metal is not seen as a second choice to virgin copper.

Recycling is also quite profitable, even with the current carbon dioxide market in Europe. Brixlegg is an especially profitable example, since so much of its energy mix is derived from hydropower, leading to much less carbon dioxide than the average copper recycling facility. The available jobs in the recycling industry have been growing annually by 10,5 percent since the year 2000. While in the year 2000 the European Union had 229.200 jobs in the recycling industry, by 2008, there were already 512.340 jobs. (BVSE, 2013)

Naturally, there will always be a need for primary copper since losses are inevitably involved in the use of copper. For example, when used in infrastructure, a certain amount of copper will be eroded. Therefore, the primary copper industry will still find plenty of demand not only due to erosion but also due to newly industrialized countries such as China, which have increased their demand incredibly over the past years. With an increase in personal wealth in countries like China, India and Brasil, there is an increase in demand for products like cars, containing between 25 to 50 kg of copper, and trains, containing 10 tonnes of copper. According to the International Copper Study Group, copper demand has risen by 250 percent since 1960, and 44,8 percent of Europe's copper originates from recycled copper (Recycling Magazine, 2012). The rise in demand of copper will also clearly lead to a rise in the recycling of this valuable material.

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