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EVALUATION OF THE INTEGRATION OF SOLAR AND MINING INDUSTRIES THROUGH A LIFE CYCLE ASSESSMENT

MEMORIA PARA OPTAR AL TÍTULO DE INGENIERO CIVIL QUÍMICO

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SUMMARY

RESUMEN DE LA MEMORIA PARA OPTAR AL TÍTULO DE:
Ingeniero Civil Químico
AUTOR: Simón Moreno Leiva
FECHA: 7 de Abril de 2016
PROFESOR GUÍA: Felipe Díaz Alvarado

EVALUATION OF THE INTEGRATION OF SOLAR AND MINING INDUSTRIES THROUGH A LIFE CYCLE ASSESSMENT

This work reports the application of the Life Cycle Assessment (LCA) technique to the analysis of the main copper production processes in the Chilean context. The goal of the study was to estimate the environmental benefit, in terms of Global Warming Potential (GWP), that can be achieved with more intensive use of solar technologies to produce energy for the Chilean mining industry. Specifically, the copper industry and its GWP are the focus of the work.

A baseline for current GWP of pyro and hydrometallurgical copper processes was built, using 2014 average data for the Chilean industry. Pyro-processes are estimated at 4.901 [$kgCO_{2eq}(ton\ Cu)^{-1}$] and hydro-processes at 3.960 [$kgCO_{2eq}(ton\ Cu)^{-1}$]. Most of the overall Green House Gases (GHG) emissions for each type of process are electricity-related (87% in pyro-process and 76% in hydro-process).

Photovoltaic (PV), Concentrated Solar Power CSP, and solar thermal technologies were assessed. For pyro-process GWP decreases 10% when integrating PV and 35% when integrating CSP. And for hydro-process GWP decreases 14% with PV, 48% with CSP and 4% when employing solar thermal technology.

The highest GWP reduction is achieved when both CSP and solar thermal technologies are integrated in hydro-process. 2.090 [$kgCO_{2eq}(ton\ Cu)^{-1}$] are saved and GWP of this process decreases 53%.

Suggestions for future steps of this research are: perform technical feasibility and economic evaluations of proposed alternatives, evaluation of other mixed technologies scenarios, improving *process step-resolution* in the models, and adopting a *process-comprehensive approach* (understanding the purpose of every energetic resource in the process). This will allow to achieve a better comprehension of the processes under study and propose new alternatives for solar technology integration in mining industry.

RESUMEN EJECUTIVO

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EVALUACIÓN DE LA INTEGRACIÓN DE LAS INDUSTRIAS MNERA Y SOLAR USANDO LA HERRAMIENTA DEL ANÁLISIS DE CICLO DE VIDA

El presente trabajo da cuenta de la implementación del método de Análisis de Ciclo de Vida (LCA, por su sigla en inglés) a los principales procesos productivos del cobre en el contexto chileno. El objetivo de este trabajo es estimar el beneficio ambiental que se podría alcanzar con un uso más intensivo de tecnologías solares en la industria minera nacional. Específicamente, el trabajo se enfoca en el potencial de calentamiento global (GWP por su sigla en inglés) de la industria de cobre.

Se construyó una línea base para el GWP de los procesos piro e hidrometalúrgicos, considerando las condiciones actuales y empleando datos promedios para la industria chilena para 2014. Las emisiones del proceso pirometalúrgico se estiman en 4.901 [$kgCO_{2eq}(ton\ Cu)^{-1}$] mientras las del hidrometalúrgico en 3.960 [$kgCO_{2eq}(ton\ Cu)^{-1}$]. La mayoría de las emisiones totales de Gases de Efecto Invernadero para cada tipo de proceso provienen de la generación eléctrica (87% en pirometalurgia y 76% en hidro).

Se evaluaron las tecnologías fotovoltaica (PV), solar de concentración (CSP) y solar térmica. La mayor reducción del GWP se logra al integrar CSP y solar térmica en el proceso hidrometalúrgico. Se dejan de emitir 2.090 [$kgCO_{2eq}(ton\ Cu)^{-1}$] y el GWP disminuye en un 53%.

En pirometalurgia GWP disminuye 10% cuando se integra PV y 35% con CSP. Y en hidrometalurgia GWP disminuye 14% con PV, 48% con CSP y 4% con solar termal.

Para los próximos pasos en la investigación se sugiere: realizar análisis económicos y de factibilidad técnica para las alternativas propuestas, evaluar la utilización de otras combinaciones de tecnologías solares, aumentar la resolución en etapas con la que se representa las líneas productivas y adoptar un enfoque de comprensión del uso de los recursos energéticos en el proceso (*process-comprehensive approach*). Esto permitirá lograr una mejor comprensión de los procesos en estudio y proponer nuevas alternativas para la integración de tecnologías solares en minería.

DEDICATORIA

Sin contemplar proporciones entre mi gratitud y el contenido de este trabajo, sólo aprovechando la instancia, con mucho cariño a todas las personas de quienes estoy agradecido.

A mi familia que, aunque poco ortodoxa, es un refugio y tiene amor. A mis papás Juan y Tamara que me trajeron y me cuidaron, y a mis hermanos Pablo, Sara y Amelia que nos tenemos. A mis abuelos Polibio, Mercedes, Hernán y Mary.

A la Marce que me acompaña y me cuida. Recorrer es más fácil con ella. Y a su familia que me ha acogido.

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A mis amigos, que hacen todo más lindo. A mis amigos de la vida Manel, Matías, Fede, Javi, Tomás, Rosario que pueden desaparecer pero siempre están (como el Piga que casi se me olvida) y a sus respectivas familias por el cariño y la comida. A los integrantes de la gloriosa cordada de los guarenes de altas cumbres.

A los amigos de la u, los que sufrimos juntos al principio (mención especial para Schoringuer F.C.), los que nos acompañamos en la especialidad, y los que nos pillamos al final y que casi dan ganar de seguir en la u. Pero no. Son todos grosos.

A todos quienes han tenido la voluntad de enseñarme algo. Profesores del colegio, de la u, del yoga y profesores de la vida.

Al Diego, mi primo y mi amigo que está en el cielo.

A la pachamama, a los árboles, las montañas y los ríos. Porque nos dan vida y los tenemos que cuidar.

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NOMENCLATURE

In this document commas (,) have been used as thousands (1000) separators.

COCHILCO: Comisión Chilena del Cobre

CODELCO: Corporación Nacional del Cobre de Chile

CO_{2eq}: Carbon dioxide equivalent (amount of CO_2 that would have the same GWP)

CSP: Concentrated Solar Power

GHG: Green House Gases

GW: Giga Watt

GWP: Global Warming Potential (in this study measured in a timescale of 100 years)

GWh: Giga Watt hour

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

LCA: Life Cycle Asessment

MAPS Chile: Mitigation Action Plans Chile

Mtoe: Mega tonne equivalent

PV: Photovoltaics

SING: Chile's northern power generation and transmission system

Tcal: Tera calorie

1. INTRODUCTION

1.1. WORLD ENERGY SCENARIO

Global energy demand is expected to grow 37% by 2040, according to estimations from the International Energy Agency (IEA). These estimations consider that growth in global demand slows down markedly from more than 2% per year (last two decades) to 1% after 2025, as *a result both of price and policy effects, and a structural shift in the global economy towards services and lighter industrial sectors*. Also, energy supply mix on 2040 is expected to be composed by four similar parts of oil, gas, coal, and low carbon sources, which availability is not expected to be a constraint over this period [1].

Of the many types of energy demanded, electricity is the final form of energy which grows the fastest and it is the power sector the one which is expected to reduce more significantly the use of fossil fuels. Around 7,200 GW of capacity should be built in order to satisfy the expected demand until 2040 [1].

According to expert's opinions, in order to be able to supply the amount of energy that is projected to be demanded *industry and governments have no choice but to develop all sources available, including renewables in a responsible and sustainable way* [2].

1.2. CLIMATE CHANGE AND GREENHOUSE GASES EMISSIONS

The use of fossil fuels in the world has been increasing for many years, as shown in **Figure 1** [3], where the amounts are shown in million tonnes of oil equivalent (Mtoe)(amount of energy equivalent to the energy released by burning one tonne of oil):

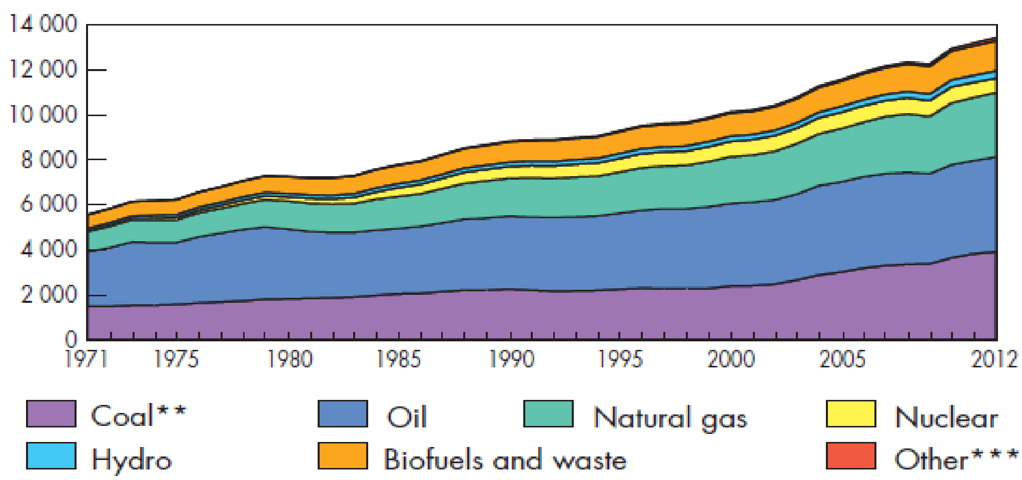


*Figure 1: World historic primary energy supply, taken from International Energy Agency IEA, «KeyWorld 2014,» [3] *Includes international aviation and international marine bunkers **Peat and oil shale are aggregated with coal ***Includes geothermal, solar, wind, heat, etc.*

This is a worrying situation, taking into account that the projected composition of the energy supply mix, as mentioned above, is intensive in fossil fuels. This scenario implies a growth of one-fifth in energy-related carbon dioxide emissions by 2040, leading to an increase of 3,6°C in global temperature, which is above the temperature rising internationally agreed goal of 2°C [1]. This goal would be achieved if the emission of carbon dioxide from 2014 onwards is below 1,000 gigatonnes, according to an Intergovernmental Panel on Climate Change's (IPCC) estimation [1].

This goal tries to solve the climate change problem, internationally recognized as a worrying issue. IPCC 2014 synthesis report indicates:

> *"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems. (...) Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen*" [4].

The main amount of all the greenhouse gases (GHG) emitted correspond to carbon dioxide produced in fossil fuel combustion and industrial processes. During 2010, 49 gigatonnes of carbon dioxide equivalent of GHG were emitted and 65% came from the above mentioned sources [4]. In this context, renewable energies appears as a critical element of the low-carbon pillar of future global energy supply and are expected to account for almost half of the electric capacity growth to 2040 [1].

In this sense, Fatih Birol, Chief Economist and incoming Executive Director of the IEA, explained that energy sector must cut emissions while powering economic growth, boosting energy security and increasing energy access [5].

1.3. Chilean energetic scenario

In 2012, Chile's final consumption of energy resources was composed as shown in **Figure 2**.

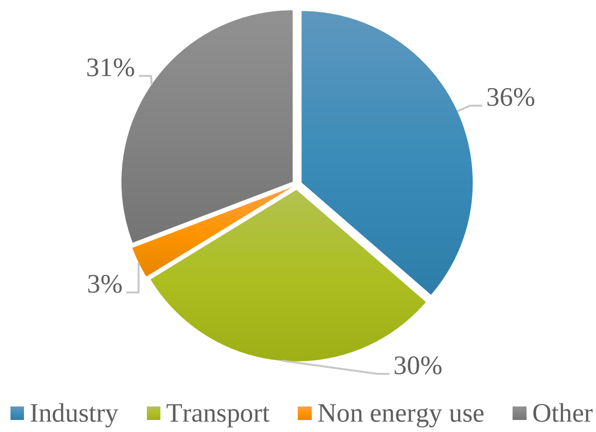


Figure 2: Final energy resources use in Chile 2012. From IEA's energy balance flows data [6]

The total of energy resources consumed in the country during 2012 was 24.95 millions of tonnes of oil equivalent [6], composed by the mayor types of energy shown in **Figure 3**.

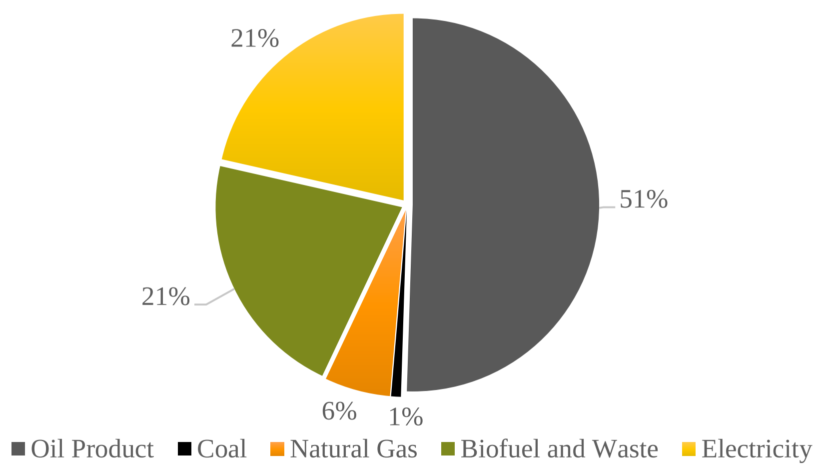


Figure 3: Type of Energy Resource in the Final Consumption 2012 in Chile. From IEA's energy balance flows data [6]

Particularly, for electric generation, which as above mentioned is the demanded form of energy which grow the fastest, the sources (divided in conventional and non-conventional renewables) used in Chile during July 2015 are shown in **Figure 4**.

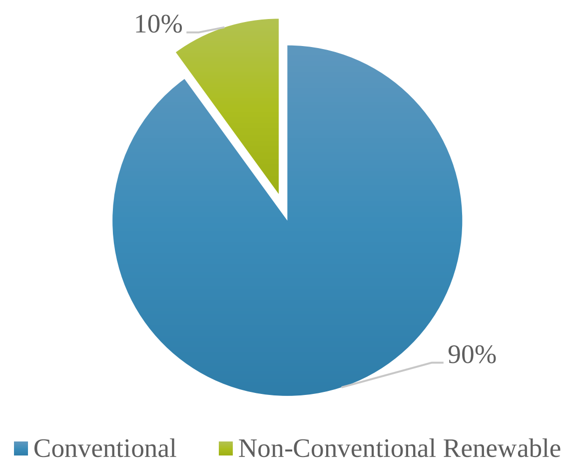


Figure 4: Conventional and Non-Conventional Renewable Electricity Generation in Chile. From CIFES August 2015 Report data [7]

Where non-conventional renewables includes solar, power from wind, mini-hydro (below 20MW) and biomass generation. The total power generation during the month used as example (august 2015) was 6,163 GWh, with 617 GWh produced with non-conventional renewables.

1.4. Chilean Mining Industry's Energetic Scenario

In Chile high amounts of energy are needed by the mining industry. This energy is supplied in different forms. It can be calculated from *Balance Nacional de Energía 2013 (National Energy Balance 2013)* that the total amount of energy consumed by mining industry during 2013 was 40,921 tera calories, divided as shows **Figure 5** [8]. This amount implies a power demand of 5.43 GW which accounts for a 9% of the country's total energy demand for that year (60.78 GW).

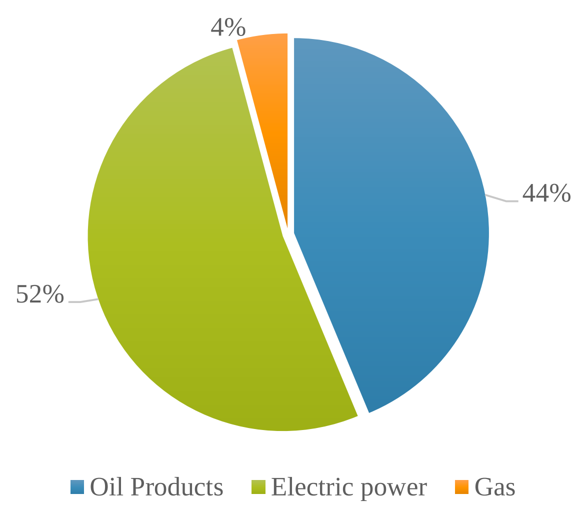


Figure 5: Forms of Energy in Mining Industry in Chile 2013. From data from Balance Nacional de Energía 2013 [8]

In order to achieve a better understanding of the energy sources used in mining industry, electric generation process should be analyzed. As mentioned, most of generation in Chile is based in conventional technology, while non-conventional renewables account for a smaller portion. Particularly, in the north of Chile, where most of the mining activity is concentrated, the distribution of the sources used during July 2015 was as shown in **Figure 6**.

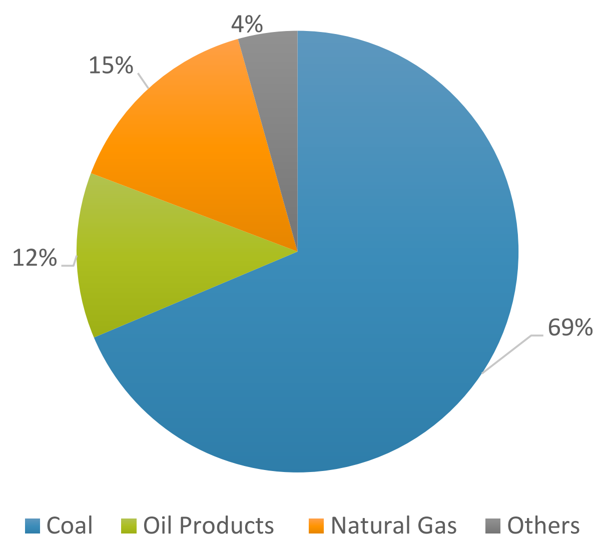


Figure 6: Electric Generation in the North of Chile July 2015. From Informe Mensual a la CNE Julio 2015 by CEDEC-SING [9]

These data correspond to Chile's northern electricity generation and transmission system (SING). The total amount of electricity generated in July was 1,548 GWh. "*Others"* includes co-generation, hydroelectric and solar production, being the solar contribution the most important [9]. With all information mentioned above about how energy is supplied to the mining industry in Chile, it's possible to conclude that there is a strong dependence on fossil fuels. This dependence implies, among others disadvantages, high emissions of greenhouse gases.

1.5. Chile and the Climate Change

Nowadays Climate change is a concern in Chile [10]. In this sense, planning efforts are being done by central government. An example of this is the Mitigation Action Plans MAPS Chile project, which aims to identify and analyze different climate change mitigation scenarios and its consequences in future. One conclusion of this work is that carbon dioxide equivalent (CO_2eq) emissions can be reduced in 4.1 to 16.8 million tonnes of CO_2eq in relation with the developed base line, depending on the implemented mitigation policies [11]. These results show that there are actions which can reduce future greenhouse gases emissions and have a positive impact in climate change mitigation.

1.6. SolarMining project

This is a joint project of the *Universidad de Chile's Centro de Energía (CE)* and the Universität Stuttgart's *Institut für Energiewirtschaft und Rationelle Energieanwendung (IER)*, which goal is to assess the integration of solar technologies (and its associated industry of energy generation and parts construction) and the mining industry in the north of Chile in order to develop a roadmap towards a more sustainable solar and mining industry.

The International Energy Agency state that, in order to change the global energy trends, well informed policy-makers are required [1]. Solar Mining project aims at achieving good quality information sources for relevant stakeholders in the energy and mining industry.

To achieve the above mentioned goal, the project is going to develop four specific objectives:

- Diagnosis of the current mining situation: Determine current energetic demand of the different mining processes in the Atacama Desert, status of northern Chile's energy system and how can solar technologies deal with the aggressive mining environment.
- Life Cycle Assessment: Estimate the environmental impact of Solar Mining (understood as the symbiotic interaction of solar technologies and mining processes) implementation from a product's whole life cycle perspective.
- Economic Assessment: Estimate cost and benefits of solar technology implementation and determine how Solar Mining can assist competitiveness of mineral extraction.
- Roadmap for Solar Mining: Define the most suitable pathway to deploy Solar Mining, identify the gaps for its implementation and determine how relevant it is for the future of mining in Chile.

1.7. THESIS' GOALS

In the context of Solar Mining Project, this work aims to investigate how solar technologies can contribute lowering mining industry's GHG emissions in Chile.

The projected product of this particular thesis work is to estimate how much environmental benefit can be achieved with more intensive use of solar technologies in the mining industry. This, applied for some particular examples of solar-mining interactions. Thus, the thesis work is going to contribute achieving the first two Solar Mining project's specific objectives.

1.7.1. MAIN GOAL

The main goal of this thesis is to assess the environmental consequences of the integration of solar technologies and mining processes for specific applications in the north of Chile context, as a result of the application of the Life Cycle Assessment (LCA) evaluation method.

1.7.2. SPECIFIC GOALS

- SG1: Review and filter the available information.
- SG2: Decide which specific mining processes-solar technologies interactions are going to be assessed in this work.
- SG3: Model and simulate the processes with focus on energy consumption and GHG emissions.
- SG4: Evaluate the pertinence of the selected interactions using the LCA tool.

1.8. SELECTION OF INDUSTRY TO ASSESS

Copper processes were chosen to be assessed in this study, as the first approach to the application of LCA method in the context of the Solar Mining project. This decision is based on both the economic and energetic relevance of the copper industry Chile.

First, to illustrate the economic relevance of the copper industry, **Figure 7** shows how this industry has contributed to Chilean gross domestic product (GDP) from 2011 to 2014. **Figure 7** also compares the contribution of copper industry with the contribution of the rest of the mining industry (iron, nitrates, etc.).

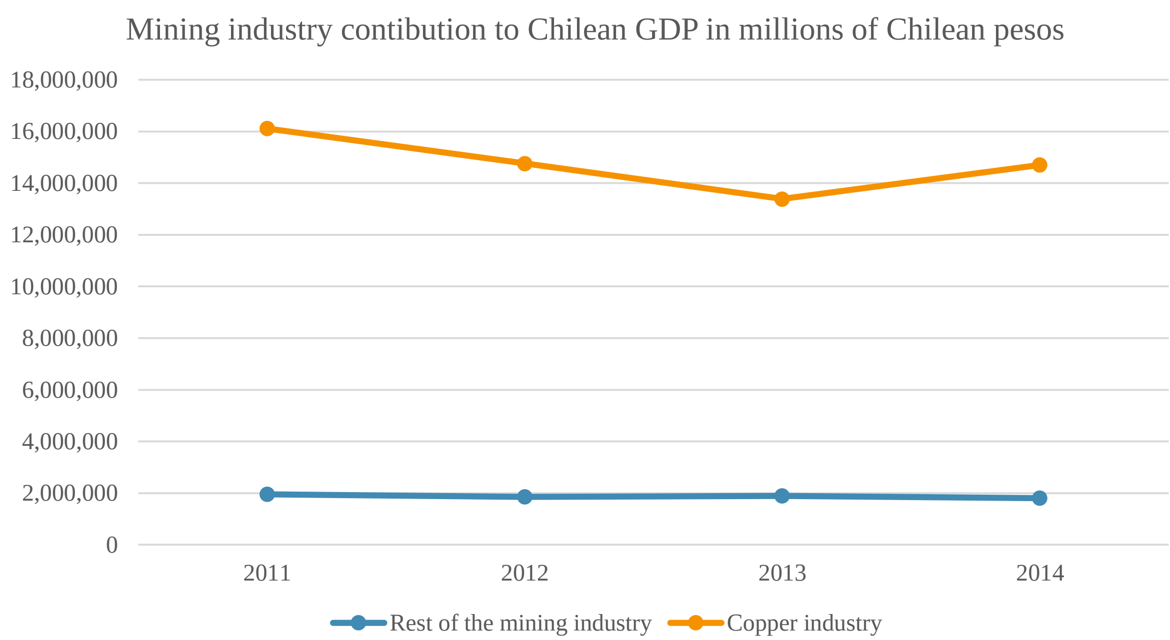


Figure 7: Mining industry contribution to Chilean GDP. From data in COCHILCO [12]

On the other hand, the relevance of the primary energy consumption of this industry is shown in **Figure 8**, where copper industry is compared with the rest of the mining industry in terms of energetic demand. As shown, 85% of the energy consumed in mining is used to produce copper. The Chilean mining industry demanded 40,921 Tcal in 2013 [13].

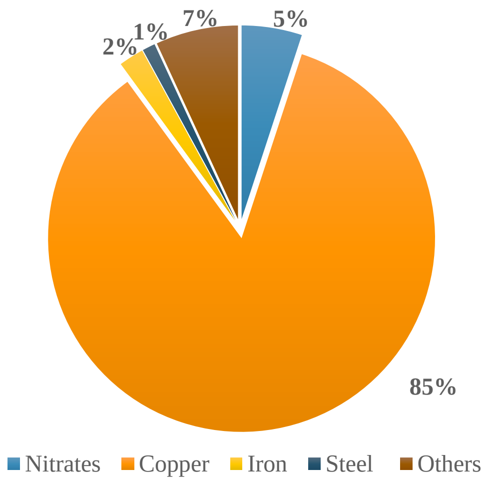


Figure 8: Chilean mining industry energy consumption shares for 2013. Prepared with Balance Nacional de Energía from Chilean Ministry of Energy data [13]

1.8.1. COPPER PROCESSES DESCRIPTION

There are two main processes to produce copper from ores. The selection of the process depends on the type of ore.

When processing copper-iron-sulfide and copper-sulfide minerals, concentration, smelting, and refining operations are mostly used [14]. These consecutive operations are going to be referred as pyrometallurgical process (pyro-process).

When processing oxidized minerals, leaching, solvent extraction, and electro-wining operations are commonly used [14]. These consecutive operations are going to be referred as hydrometallurgical process (hydro-process).

Figure 9 and **Figure 10** show a representation of both copper processes. Further detail about these process chains can be found at **Appendix 1: Copper processes description**.

Some relevant energy inputs of the ones that have been identified beforehand are presented here. Naturally, there are several more energy inputs in every process-step and they were included in the study as explained in methodology section of this report. Diesel is the most demanded fossil fuel in the mining industry. Diesel is mostly used to fuel trucks for mineral extraction. In pyro-process comminution operations have a high electric energy demand and smelting process has a relevant demand for diesel. In hydro-process electro-wining has been identified as an operation with high electric power requirements. These energy flows are also shown in **Figure 9** and **Figure 10** [14] [15].

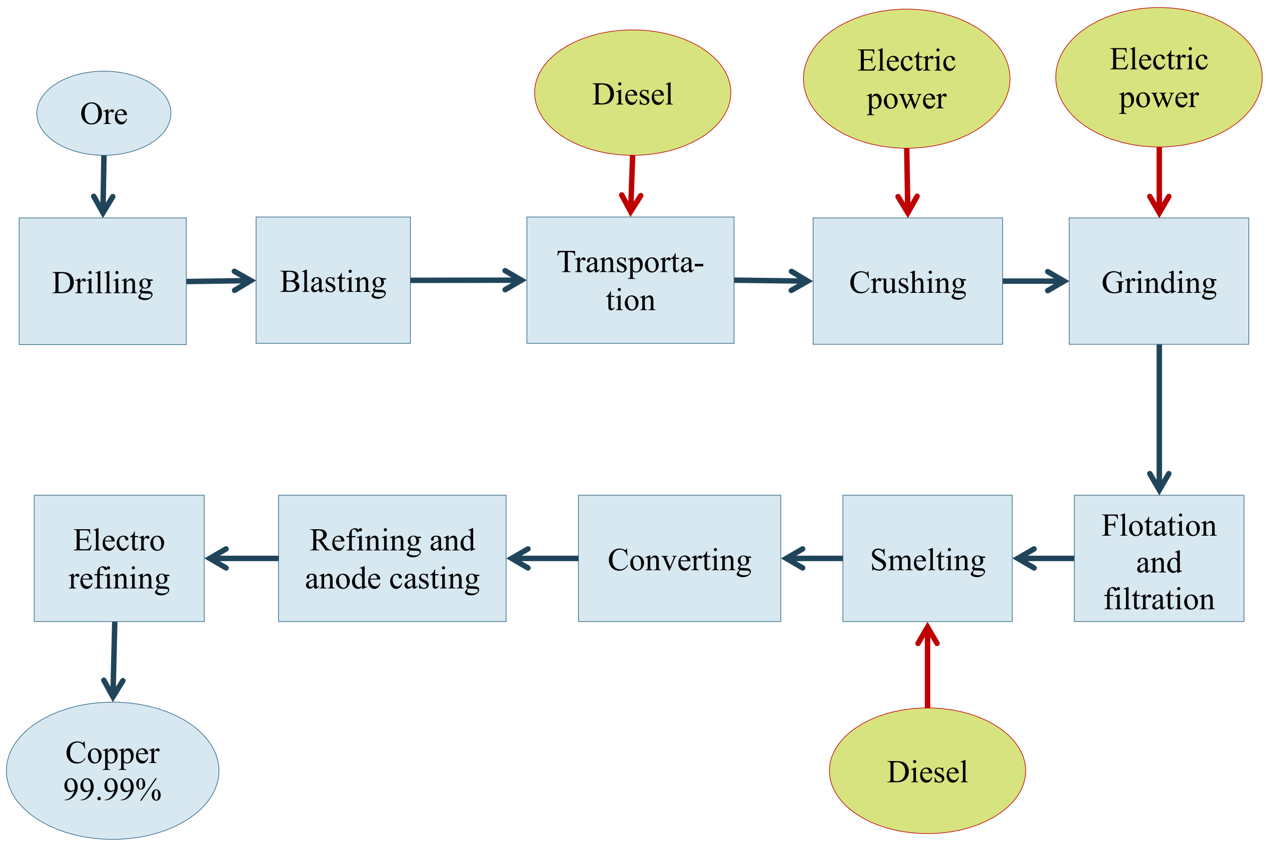


Figure 9: Copper pyrometallurgical process' general description. Based on [14] and [16]

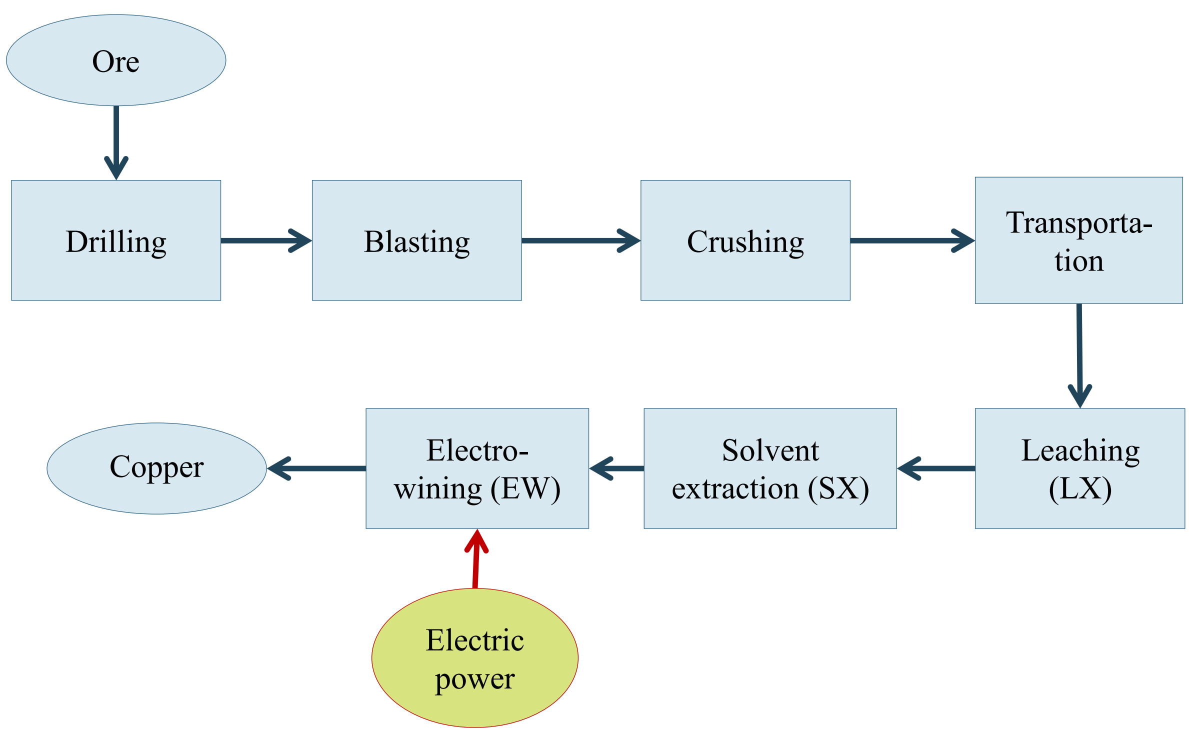


Figure 10: Copper hydrometallurgical process' general description. Based on [14] and [16]

1.9. ABOUT LIFE CYCLE ASSESSMENT

1.9.1. STATE OF THE ART OF LIFE CYCLE ASSESSMENT (LCA) METHOD

LCA is a method for assessing industrial systems, evaluating all stages of a product's life from the perspective that they are independent, meaning that one operation leads to the next. This method allows estimating the cumulative environmental impact along a whole product's life cycle. Thereby, this method enables to reach a more comprehensive view of the environmental aspects of the process and identify trade-offs in product and process selection [17].

This approach enables to identify threats and opportunities in the life cycle of a product and also to identify the stages of the process where most of the environmental impact is concentrated, thus where the modification efforts can be focused [18].

There are protocols which aim to standardize the implementation of this method, such as ISO14040 and ISO 14044 guidelines. The standard stages of a LCA are presented in **Figure 11** as shown in those guidelines [19].

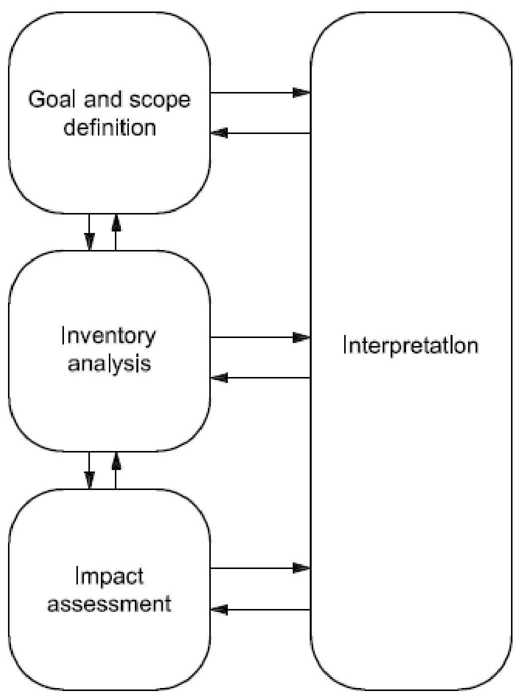


Figure 11: LCA framework [19]

In *goal definition and scope* the product (process or activity) to be assessed must be described. Also the context, system boundaries and environmental effects to assess in the study must be defined. Then, in the *inventory analysis* energy and materials usage and release to environment are identified and quantified. In the *impact assessment* stage the information from the *inventory analysis* is used to assess the human and environmental effects by assessing the impact of the process in terms of a specific impact category (such as GWP, acidification potential, etc.). The *interpretation* process aims to make decisions based on the results of both *inventory analysis* and *impact assessment* and always minding the uncertainty and assumptions made to attain these results [17].

There are six basic decisions that have to be made at the first stage of an LCA [17]. The description and/or the alternatives for these decisions (based on the information presented in [17]) are going to be presented here and the selected options for this study are presented in **section** Error! Reference ource not found..

1. *Goal(s) of the project*: Besides choosing the best product (or process or service) with the lowest human and environmental impact (primary goal of an LCA), LCA can also assist the development of new products, processes or services. Some examples of secondary goals, which depends on the type of project, are:
    - ❖ *Support broad environmental assessments*
    - ❖ *Establish baseline information for a process*
    - ❖ *Rank the relative contribution of individual steps or processes*
    - ❖ *Identify data gaps*
    - ❖ *Support public policy*
    - ❖ *Support product certification*
    - ❖ *Provide information and directions to decision makers*
    - ❖ *Guide product and process development*
2. *What information is needed to inform the decision-makers:* knowing what questions are interesting for decision makers allows a better design of the assessment. Examples of questions a LCA can help answer are:
    - ❖ *What is the impact to specific stakeholders?*
    - ❖ *Which product causes the least environmental impact (quantifiably)?*
    - ❖ *How will changes to the current process affect the impacts?*
    - ❖ *How can the process be changed to reduce a specific impact?*
3. *Required specificity:* whether the LCA should be performed in a generic or process-specific way must be decided at the beginning of the study. A study could fall in between both approaches. This decision depends on various factors, among which the following stand out:
    - ❖ *Is the process specific to one company or manufacturing operation? Or is it a common process in the industry?*
    - ❖ *Is the LCA going to be used for internal organizational or public purpose?*
    - ❖ *Data availability and quality*
    - ❖ *Availability of resources to conduct the study*

4. *How data should be organized and the results displayed:* A *functional unit* is the unit to which the results of the assessments are referred. It has to describe the function of the analyzed product or process. It also has to be carefully selected in order to be able to properly compare the results of the assessments of different options.
5. *Scope of the study:* An LCA study can include these four stages of the life of a product/process:
    - ❖ *Raw materials acquisition:* includes the removal of resources from the earth and the transportation to the processing facilities.
    - ❖ *Manufacturing:* in this stage raw materials are converted into products. This stage in its turn is composed by three stages:
        - ❖ *Materials manufacture:* transforms raw materials into a form that can be used to produce finished products.
        - ❖ *Product fabrication:* uses the manufactured materials to fabricate products ready to be packaged.
        - ❖ *Filling/packing/distribution:* includes all of the activities (production and transportation) needed to fill, package and distribute the finished products.
    - ❖ *Use/reuse/maintenance:* includes every activity associated to the use of the product during its entire useful life. Maintenance to preserve product's performance is also included in this stage.
    - ❖ *Recycle/waste management:* Includes the activities related to the disposition of the product.
6. *Ground rules for performing the work:* there are three aspects to mind:
    - ❖ *Documenting assumptions:* Every assumption must be shown when reporting LCA results to avoid misinterpretation. The assumptions and scope limitations characteristics depends on resource availability.
    - ❖ *Quality assurance procedures:* in order to guarantee the quality of the study both internal and external (to the organization performing the LCA) revisions may be carried out. The type of procedure to implements depends on the intended use of the results.
    - ❖ *Reporting requirements:* how the results are going to be presented has to be decided. The implemented methodology must be also presented along with the definition of the analyzed system and its boundaries. It is important not to oversimplify the results.

1.10. STATE OF THE ART OF LCA APPLIED TO COPPER MINING INDUSTRY

There are many LCA studies applied to mining processes. There are also LCA studies for copper processes. The most relevant ones focused on global warming potential estimation and used for the analysis in this study are summarized in **Table 1**. Comisión Chilena del Cobre COCHILCO estimations of GHG emissions from fossil fuel combustion are also presented in the table in spite of not being estimated trough LCA.

Table 1: LCA applied to copper mining studies

Description	Results		Reference
	Pyro-process emissions [$kgCO_{2eq}(ton\ Cu)^{-1}$]	Hydro-process emissions [$kgCO_{2eq}(ton\ Cu)^{-1}$]	
LCA of general pyro and hydro metallurgical copper processes	3.300	6.200	Norgate, T.E. [20]
LCA of CODELCO's processes	For Chuquicamata: 3.606	Average for Chuquicamata and Radomiro Tomic: 3.725 (calculated with data from [21])	Bustos, J. [21]
Estimation of direct emissions from fossil fuel combustion	550 (based on [22]. See **section 2.3**)	840 (based on [22]see **section 2.3**)	[22]. Data for 2014.

Pyrometallurgical and hydrometallurgical copper processes are explained in **section 1.8.1**.

It is very important to mind the assumptions made to obtain results presented in **Table 1** when using them to analyze the results of this study.

2. METHODOLOGY

In this section the strategies set to achieve the goals of the study are presented. The assumptions made to represent the processes under study are also shown.

2.1. LCA DEFINITIONS FOR THIS STUDY

The basic definitions for the LCA conducted in this study are:

1. *Goal(s) of the project*: Note that these are the goals of the application of the LCA in this study, not the mentioned goals of the whole work. Among the above listed examples of secondary goals for an LCA, the ones which better fit the aim of this study are the following:
    - *Establish baseline information for a process:* this study is a first approach on the exploration of the copper industry in the context of the SolarMining project. Then, an assessment of the emissions of the average industry (under current conditions) is done in order to build a baseline to roughly compare different alternatives to integrate solar technologies.
    - *Rank the relative contribution of individual steps or processes:* identifying the stages which contribute the most to the overall emissions of the process is necessary to decide where to focus future efforts in the exploration of new alternatives.

- ❖ *Identify data gaps:* access to information is an important issue when performing a LCA. Having a first idea of the useful information available is also an expected output of the implementation of the method in this study.
- ❖ *Provide information and directions to decision makers:* this study is expected to be a first input to design strategies to achieve the goals of the SolarMining project.

2. *What information is needed to inform the decision-makers:* answering how changes to the current process will affect its environmental impact is the aim of the LCA performed in this study. Specifically how emissions and GWP will vary when using solar technologies to supply energy to the process.
3. *Required specificity:* since this LCA aims to show results for the overall industry, the assessment is generic. Reliable average data for the copper industry is available in *Comisión Chilena del Cobre* (COCHILCO) databases [16]. Also, the processes used in copper production are similar among different companies.
4. *How the data should be organized and the results displayed:* The emissions arising from the processes are reported as kilograms of carbon dioxide equivalent per ton of pure copper. Thus the *functional unit* is one ton of copper. This unit allows easy comparison of the results since it is referred to the valuable product of the assessed processes.
5. *Scope of the study:* The stages analyzed in this study are:
   - ❖ *Raw material acquisition:* the removal of mineral from the earth is considered as the first stage of the process studied in this work. Also the transportation to processing plants is included in the analysis.
   - ❖ *Manufacturing:*
     - ❖ *Material manufacturing:* this study analyses the impacts of copper processes until the production of high purity copper cathodes. This is not a finished product but it is used to produce them.

   The next stages in the value chain are not considered in this study. More detail on how the processes have been modeled and the system boundaries defined is presented in *modelling and assumptions* section.
6. *Ground rules for performing the work:* these are the considerations for the above mentioned three points:
   - ❖ *Documenting assumptions:* the assumptions made to achieve the results of this study are presented in *modelling and assumptions* section.
   - ❖ *Quality assurance procedures:* the review process of this work was internal. There was permanent supervision from an LCA-experienced member of the SolarMining project team. There is no formal documentation of the review process.
   - ❖ *Reporting requirements:* the results are presented as kilograms of carbon dioxide equivalent per ton of copper produced. These are presented by stage of the processes and as overall emissions. Sensitivity analysis are also shown in this report. System boundaries are explained in *modelling and assumptions* section.

2.2. METHODS FOR SOLAR PLANT MODELLING

To assess the impact of the integration of solar technologies in the copper mining industry three specific technologies were included in this study: photovoltaic (PV), concentrated solar power (CSP) for electric generation, and solar thermal to produce heat. Each of these technologies is associated to one step in the copper processes. The changes in the GWP of the processes due to the integration of these technologies are reported in *results and discussion* section.

Table 2 summarizes the specific types of solar technologies assessed in this study.

Table 2: Specific technologies for solar plants

Type of solar plant	Specific technology	Reference study
Photovoltaic (PV)	Average performance of different technologies	[23]
Concentrated Solar Power (CSP)	Parabolic trough with storage	[24]
Solar Thermal	Flat plate collectors	[25]

The modelling of solar plants depends on the irradiance levels of its location, which varies significantly in time. The availability of the solar resource is not steady. Evidently, solar irradiance is not the same in day and night. There are also daily, monthly and yearly cycles. **Figure 12** illustrates this situation showing the average irradiance levels for every month during year 2011 in Calama, Chile.

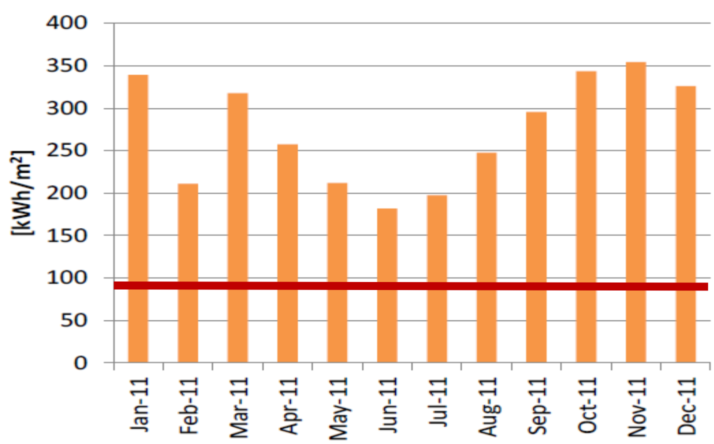


Figure 12: 2011 average irradiance levels in Calama. From SolarMining project's CSP techno-economic datasheet [24]. Based on data from [26].Red line is added to show average irradiance level in Switzerland. From Ecoinvent *report about photovoltaics [23].*

Since the LCA model is not a dynamic representation of the processes, it is necessary to calculate the energy yield of solar plants with an external tool (*Excel* in this study). Ten-minute-resolution irradiance data were processed to calculate an average irradiance per square meter per year, for a specific location. With this value, the yield of an average Swiss PV power plant (for which there were reliable data [23]) was scaled up. From *Ecoinvent* database values of emissions associated to the construction and operation of a Swiss average PV plant, as well as its yield, can be obtained.

Also from *Ecoinvent* report about photovoltaics can be obtained the value for the average Swiss irradiance level (91,7 [kWh/m^2/month]), which corresponds with these data [23].

2.3. Modelling and assumptions

The modelling process was divided in two stages. First, the development of a model to assess the GHG emissions and GWP of the copper production processes under the current conditions. The results obtained from this model and its simulations are referred as *current scenario*. Then, solar technologies for energy production were included in the processes and the new GHG emissions and GWP of the processes were estimated and compared with the originals.

The *current scenario* was represented in two different models. One for the pyrometallurgical and other for the hydrometallurgical copper process (A block diagram representation of standard configuration for these processes can be found in **Appendix 1: Copper processes)**. For both processes emissions associated with energy supply are taken into account. Emissions associated with the construction of mineral processing plants are not taken into account in this study.

The scenarios including solar technologies also consider the emissions associated with the construction of the solar plants.

The *current scenario* model contemplates (for both pyro and hydrometallurgical cases) from the extraction of the copper mineral in the mine to the production of copper cathodes. Thus, all the operations of both processes (pyro and hydro) above described are inside the borders of the analyzed system.

The emissions are classified in two categories: the ones arising from fossil fuel combustion occurring in the mining operations and the ones arising from the power generation which is taken from the grid. These emissions are referred as *fossil fuel related* and *electricity related*, respectively. Notice that, nevertheless the *electricity related* emissions are not being generated in the mining operations places but in the different power plants which supply energy to the grid, these are attributed to the operation of the metallurgical processes in this study. Thus, the on-grid electricity generation is also within the borders of the analyzed system.

The energy consumption for every step in the processes were taken from the *Comisión Chilena del Cobre* COCHILCO databases for 2014 [16]. This means that the data used in this study to characterize the energetic requirements of copper processes are yearly averages for the whole Chilean copper industry and does not correspond to any specific operation. This decision allows the study to present an overview of the whole industry, as a first approach in the context of the SolarMining project. COCHILCO data comes from surveys directly answered by mining companies and represents 98% of the Chilean copper industry [15].

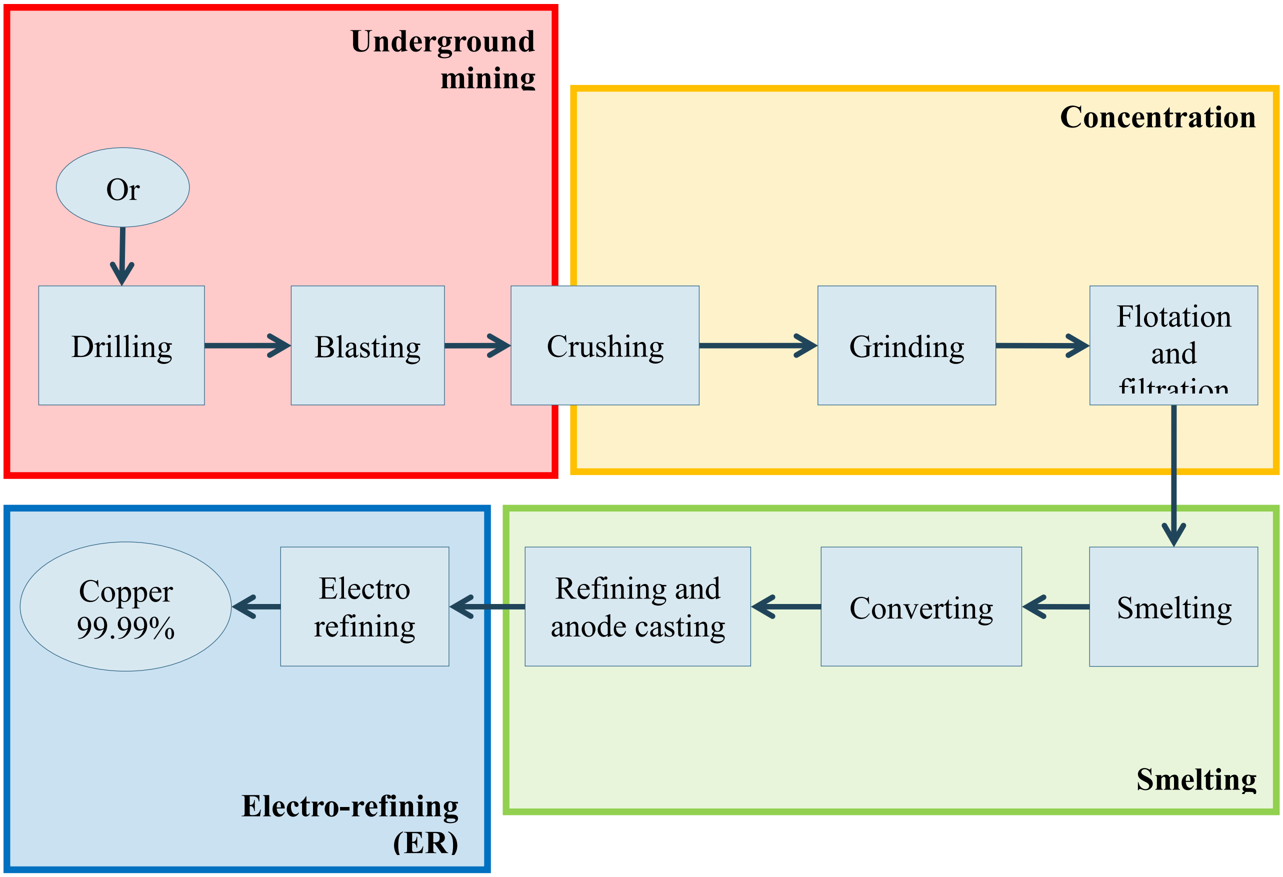


Figure 13: Pyrometallurgical copper process: operation grouping for modelling

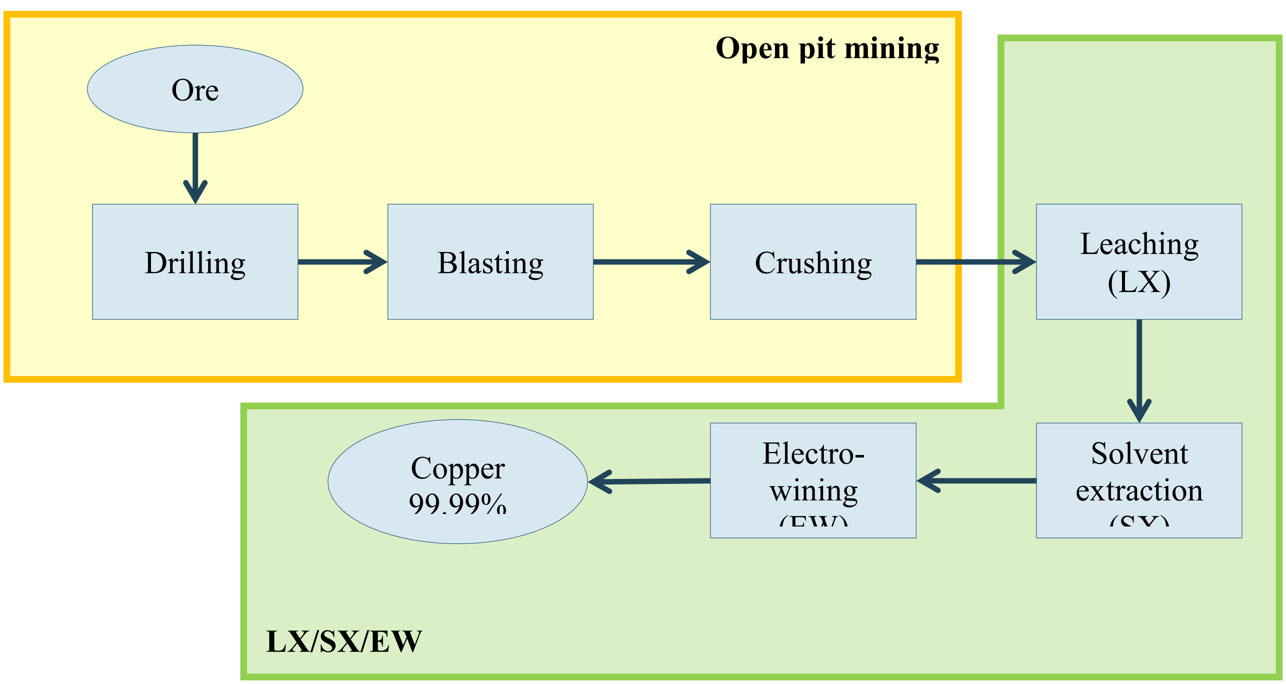


Figure 14: Hydrometallurgical copper process: operation grouping for modelling

In this study's models, the operations (steps) of copper processes are arranged the same way they are presented in COCHILCO's reports. **Figure 13** and **Figure 14** show how the model has grouped the different operations of both copper processes. Thus, the pyrometallurgical process is represented with mining, concentration, smelting and electro refining steps, while hydrometallurgical process is represented with mining operation and a process which includes leaching, solvent extraction, and electro wining steps (LX/SX/EW). **Figure 15** shows how the processes are represented in the model.

These models have a low *process-step* resolution. It means that the steps used to model the processes include many different operations. Thus, the results of the simulation will not allow to match the emissions with specific operations but only with the corresponding model's step.

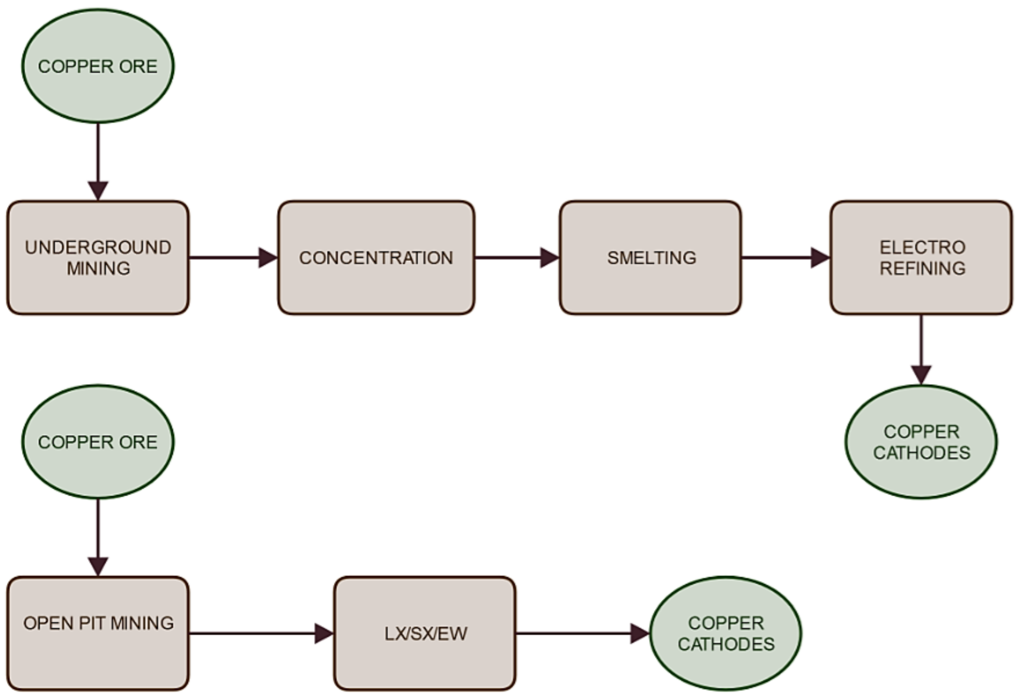


Figure 15: Pyro and hydrometallurgical processes representation

In order to enable data collection assumptions have to be made on the types of mining used in each process. Usually copper sulfides are processed via pyrometallurgical methods and coper oxides via hydrometallurgical methods [14]. Since copper sulfides are found in deeper zones, while copper oxides are found closer to the atmosphere, the following assumption was made: copper mineral feeding pyrometallurgical process is obtained in underground mining and the one which feeds hydrometallurgical process comes from open pit mining. This assumption is relevant since indicates which data to extract from COCHILCO database. It can be easily modified in the future using the LCA model developed in GaBi software.

Table 3 shows the description of every step in both copper processes.

Table 3: description of the modelled processes stages. Based on COCHILCO's definitions [16]

Step	Description
Underground mining	Unit operations needed to extract the mineral from an underground mine. Some of the most relevant operations are: drilling, blasting, transport and primary crushing.
Open pit mining	Unit processes needed to extract the mineral from an open pit mine. Some of the most relevant operations are: drilling, blasting, transport and primary crushing. (considers every operation until primary crushing)
Concentration	Includes unit operations after primary crushing. The most relevant are: crushing, grinding, flotation and filtration.
Smelting	The most relevant unit operations are: drying, smelting, converting, refining and casting.
Electro refining	It is the electrolysis process which produces high purity copper cathodes.
LX/SX/EW	Contemplates the hydrometallurgical unit operations needed to produce copper cathodes. The most important operations are: agglomeration, leaching (LX), solvent extraction (SX) and electro wining (EW).
Water and services	Represents the activities which are not involved in the main value chain of copper but are needed for the operation and have an important energy consumption level. The most relevant activities are: energy consumption at camps and machine shops and energy consumption for water pumping and desalinization.

There are some relevant considerations about *water and services* process. First, notice that notwithstanding this is not a step in the main value chain of copper production, it has a relevant energy consumption level. Although it is not represented in the shown copper processes, it is considered in the model. Thus, the operations involved in this process are inside the borders of the analyzed system. There is no specific information available on COCHILCO databases on energy requirements for water pumping and desalination. This data are aggregated with the above described *water and services* process. Relevant assumptions were made to deal with this fact: COCHILCO reports values for fossil fuels and electricity demand per ton of pure copper produced for the whole “water and services” process [16]. These values, which do not distinguish between hydrometallurgical and pyrometallurgical processes, were used in this study. Therefore, the emissions associated to the “water and services” processes only depend on the amount of copper produced and not on the process used. This is an error source which must be pondered in order to achieve appropriate conclusions.

Chile has two separated power systems. To estimate *electricity related* emissions, the average 2014 emission factor for Chile’s northern electric system (SING) was considered. Its value is 0,79 [tCO_{2eq}/MWh] (tonnes of carbon dioxide equivalent per megawatt hour generated) [27].

To estimate *fossil fuel related* emissions more assumptions were done. First, the specific types of fuels to consider were defined. The three most intensively used by the mining industry are diesel, heavy fuel oil and natural gas. Diesel is by far the most relevant, given that it represent the 85% of the fossil fuel demand of the industry [15]. The amount of diesel consumed in every step of copper processes is reported by COCHILCO (in energetic units). Nonetheless the amounts of heavy fuel oil, natural gas and other fuels demanded in the different steps are not reported.

To determine how much energy comes from fossil fuels different from diesel, the overall share of every fossil fuel in the mining industry’s consumption was taken into account. The difference between the amount of energy coming from diesel and the amount of energy coming from the others fossil fuels was calculated for every process. Then, the composition of this difference was assumed as a mix of heavy fuel oil and natural gas. The shares of each fuel in this mix were calculated using approximately the same ratio that the shares of these fuels have in the overall mix. Further detail about these calculations can be found in **Appendix 2: Fossil fuel shares estimations**.

Then, the combustion process for each of the three fuels included in this study was modeled. To do this, the different processes were selected. For diesel combustion a process of burning in building machine (burning in engine) was used. For heavy fuel oil, it was considered to be burned in a power plant, while natural gas was considered to be used to run a gas turbine. These definitions are justified on both the information availability for this study and the description of the main uses of these fuels presented by COCHILCO [15]. The data used to model fuel combustion processes were obtained from *Ecoinvent* database.

As mentioned in *methods for solar plant modelling and integration in LCA* section, three types of solar technologies for energy production were included in this study, each of which is coupled to a specific process stage. Each one of these interactions configures one assessed *solar technology integration scenario*. A scenario including more than one technology is also evaluated.

The selection of the scenarios to assess depends on the features of the supplied process stage. Knowing which type of energy is required and what it is needed for, allows to decide whether an alternative is technically suitable or not. When suppling electric power not much detail about the process is needed to configure the interaction (in a first rough approach). When suppling heat further detail about the technical features of the process is required (e.g. temperature range). Minding these facts and the resources available, the scenarios to simulate were decided.

Selected electric power generation solar technologies assessed in this study were matched to the process stages with the highest demand in each type of process (pyro- and hydro-metallurgical). Solar thermal technology was matched to the process stage where technical feasibility is supported by currently operating facilities.

Table 4 summarizes the different *solar technology integration scenarios* assessed in this study.

Table 4: Solar technology integration scenarios

Scenario	Copper process	Stage supplied	% supplied with solar technology
Photovoltaic (PV) electric generation integration	Pyrometallurgical	Concentration	22% of electric demand
	Hydrometallurgical	LX/SX/EW	22% of electric demand
Concentrated solar power (CSP) electric generation integration	Pyrometallurgical	Concentration	75% of electric demand
	Hydrometallurgical	LX/SX/EW	75% of electric demand
Solar-thermal heat generation integration	Hydrometallurgical	LX/SX/EW	85% of diesel demand
Combined scenario (CSP and solar-thermal)	Hydrometallurgical	LX/SX/EW	75% of electric demand and 85% of diesel demand

The procedure of defining the assumptions about the amount of energy solar technologies are going to supply is different for each scenario. For PV technology it was assumed that a plant with nominal power equal to coupled process stage power demand is built. Then real power generation under San Pedro de Atacama's irradiance levels (estimated using data from *campaña de medición del recurso eólico y solar* [26]) is calculated. Finally the percentage of energy supplied with PV is the proportion between real solar generation and process' stage electric demand. More detail about these calculations can be found in **Appendix 3: PV yield under northern Chile irradiance conditions**.

For CSP the amount of energy which the technology could supply is based on Telsnig's estimations [24] for the performance of this kind of plants under northern Chilean weather conditions: again it was assumed that a plant with rated capacity equals to coupled process stage power demand is built, but this time the capacity factor estimated by Telsnig (75%) was directly applied. And finally the percentage of diesel replaced by heat supplied with solar thermal plant is assumed to be equal to CODELCO's Pampa Elvira plant case [28]. This plant supplies thermal energy to Gaby division's electro-wining process.

The aim of the exposed definitions about solar plants is to assess them in the north of Chile context. *Ecoinvent* database is used to assess emissions of solar plants. Solar plants' GHG emissions are due to construction phase. This emissions are allocated by plants' life span and energy yield. *Ecoinvent* does not have data for solar plants in South America so European data was used to estimate emissions associated to plant construction (except for CSP where Telsnig's assessments for a plant located in Calama [24] were included). Notice that Chilean solar irradiance levels are contemplated to estimate plants' sizes.

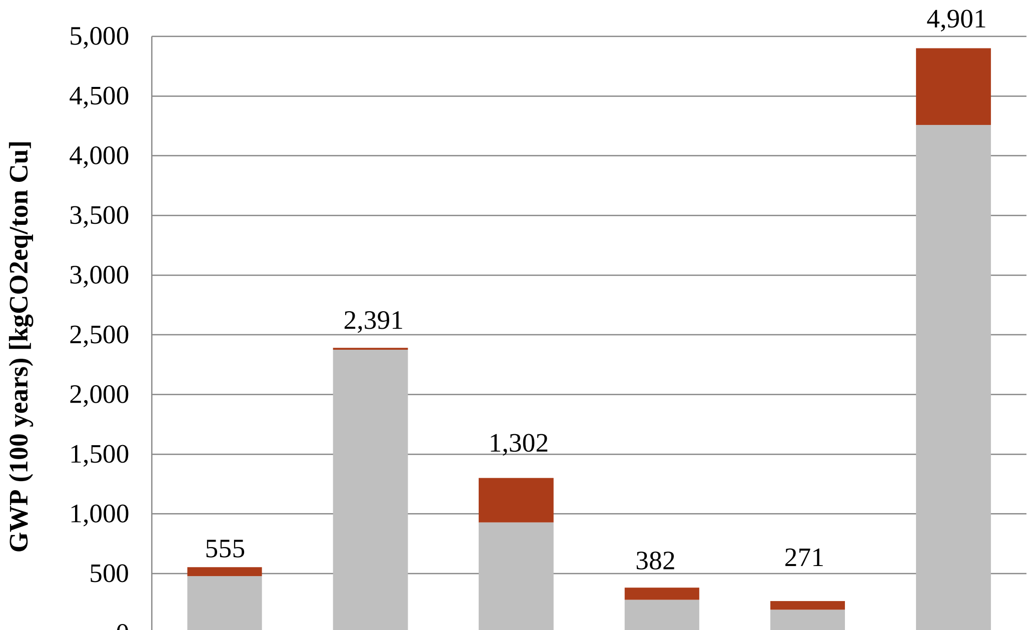
Since carrying out both Life Cycle Inventories LCI and Life Cycle Impact Assessment LCIA involves high data processing capacity, the processes and scenarios described in this section were modeled in LCA software *GaBi 4.* The graphic representation of the models implemented in GaBi software can be found in **Appendix 4: GaBi models**. These models were used to simulate both *current* and *solar technology integration* scenarios.

Once the inventories are ready the impact assessment has to be performed. The selected impact category for this study is Global Warming Potential GWP. The selected impact assessment method to calculate it is CML2001 (Center of Environmental Science of Leiden University) GWP with 100 years scope in its November 2009 updated version (the latest available in the employed software).

3. RESULTS AND DISCUSSION

3.1. CURRENT SCENARIO

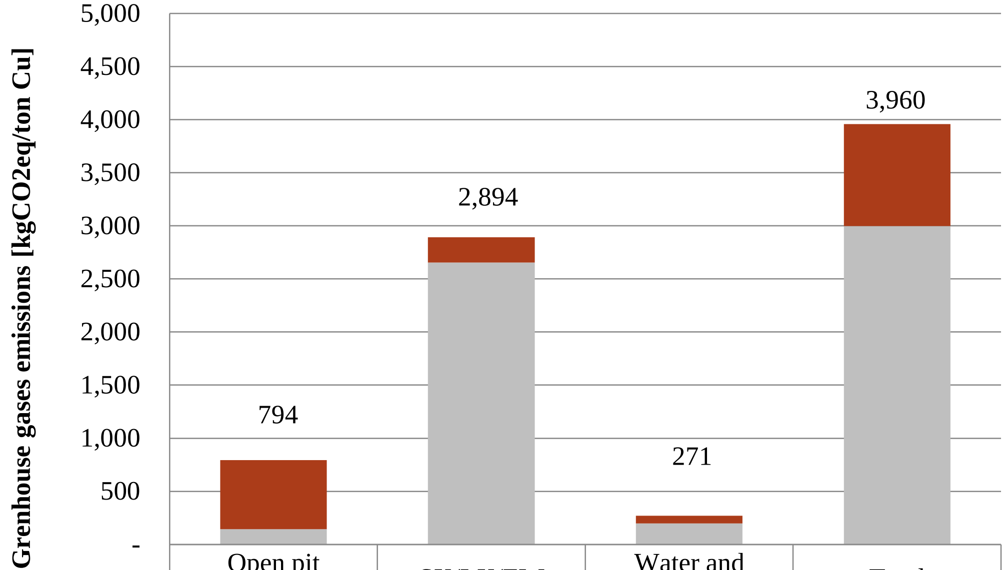
The results obtained from the LCA performed for the current scenario of the copper industry in Chile are summarized in **Figure 16** for pyrometallurgical process and **Figure 17** for hydrometallurgical process.



	Under-ground mining	Concen-tration	Smelting	Electro refining	Water and services	Total
Fossil fuels related emissions [kgCO2eq/ton Cu]	77	17	374	101	73	643
Electricity related emissions [kgCO2eq/ton Cu]	478	2,374	928	281	198	4,258

Figure 16: GWP of pyrometallurgical process for current energy supply scenario

The overall emissions for pyrometallurgical process (pyro-process) are 4,901 kilograms of carbon dioxide equivalent per ton of pure copper produced [$kgCO_{2eq}(ton\ Cu)^{-1}$] while for hydrometallurgical (hydro-process) process are 3,960 [$kgCO_{2eq}(ton\ Cu)^{-1}$]. Electricity related emissions (produced when burning fuel at the grids' power plants) have the biggest share of the overall GWP in both pyro- and hydro-processes. 87% of the emissions are electricity related in pyro-process and 76% in hydro-process.



	Open pit mining	SX/LX/EW	Water and services	Total
Fossil fuels related emissions [kgCO2eq/ton Cu]	650	240	73	963
Electricity related emissions [kgCO2eq/ton Cu]	145	2,654	198	2,997

Figure 17: GWP of hydrometallurgical process for current energy supply scenario

These results suggest that special attention should be given to electricity generation processes. Electricity related emissions are not produced in the mining operation but in electric system's power plants. In spite of that, the emissions are due to the energy requirements of mining industry.

It is also important to mind the high value of the emission factor for Chile's north electric system (SING). As shown in *Chilean Mining Industry's Energetic Scenario* section, SING is mainly composed by fossil fuel power plants, being coal the most relevant fuel. 2014 SING's average emission factor was 0,79 [$tCO_{2eq}(MWh)^{-1}$] [27].

Minding these facts the evaluation of cleaner technologies for electricity generation should be a priority when trying to reduce copper industry's GHG emissions.

Comminution processes in pyro-process and electrowinning in hydro-process demand high amounts of electricity. This explains why *concentration* and *LX/SX/EW* (which consume 10,810 and 12,086 mega joules per ton of copper processed [16]) have the highest CO_{2eq} emissions in its respective processes.

T.E. Norgate reports GWP of 3.3 [$kgCO_{2eq}/kgCu$] for pyro-process and 6.2 [$kgCO_{2eq}(ton\ Cu)^{-1}$] for hydro-process [20]. This results have similar magnitude with this study's results (4,901 [$kgCO_{2eq}(ton\ Cu)^{-1}$] and 3,960 [$kgCO_{2eq}(ton\ Cu)^{-1}$] for pyro- and hydro-processes). Chilean mining industry shows higher GWP for pyro-process than for hydro-process. Notice that it makes sense for both processes (pyro and hydro) to have different emissions levels. This, since the operations involved -and therefore the energy requirements- are very different, as shown in **section 1.8.1**.

Differences in the results can be attributed to the different data sources used to build life cycle inventories. This study uses average data from Chilean industry only, while Norgate's article does not report its data source. This last fact adds difficulty to the comparison and analysis of different results and puts in evidence the usefulness of explicitly reporting data sources and assumptions when communicating LCA results.

Another fact to mind when comparing Norgate's results is that -as shown in this study- in pyro-process electricity related emissions account for a bigger share than in hydro-process. Then the SING's emission factor being very high has a greater impact on pyro-process emissions. This could partially explain why in Norgate's study reports bigger GWP for hydro-process. This, assuming Norgate uses a lower emission factor for electricity generation processes. Again, the lack of information about Norgate's assumptions impairs the analysis possibility.

A LCA of CODELCO mining company activities was performed by Bustos, J. in 2011 [21]. The average GHG emissions reported in that study for hydro-processes connected to SING (Chuquicamata and Radomiro Tomic) are 3,725 [$kgCO_{2eq}(ton\ Cu)^{-1}$] (excluding inputs-related emissions and including energy related emissions). This amount is very similar to the one calculated in this study and shows consistency since it considers the same type of emissions this study does.

For pyro-process J. Bustos reports emissions of 3,606 [$kgCO_{2eq}(ton\ Cu)^{-1}$] for Chuquicamata operation [21]. This amount is lower than the one calculated in this study for an average pyro-process. This is more striking if we consider that the emission factor for SING used in that study is 812 [tCO_{2eq}/GWh] while for this study the factor is 790 [tCO_{2eq}/GWh]. In spite of this it is important to mind that CODELCO's LCA results correspond to 2005 operation while the present work uses 2014 data to make its estimations. Both the change in operative conditions between 2005 and 2014 and the fact that this study analyzes overall industry averages while [21] analyzes specific processes can explain the differences in the results.

When comparing Bustos' results it can be concluded that the magnitude of the estimations in this work are accurate. But special attention should be given to pyro-process GWP estimation since it is higher than both Norgate and Bustos' results.

COCHILCO also estimates emissions directly released by mining operations due to fossil fuel combustion [22]. These emissions are reported by process stages. Adding them by this study's definitions of pyro- and hydro-processes emissions of 550 and 840 [$kgCO_{2eq}(ton\ Cu)^{-1}$] are obtained. Naturally these emissions are much lower than the ones estimated in this study since they do not include electricity-related emissions. This study considers electricity-related emissions since it aims to achieve a broader approach to GWP estimation process.

But when adding fossil fuel related emissions estimated in this work GWP of 642 and 963 are obtained for pyro- and hydro-processes. These results have similar magnitude since the employed data source is roughly the same. The differences are explained by the different estimation methodologies employed in COCHILCO's and this study. In COCHILCO's study direct emission factors for different fossil fuels are applied. In this study the combustion processes are modelled with life cycle inventories from *Ecoinvent* databases and integrated in LCA GaBi model for copper processes. Thus, although the data about energy consumption is the same, the procedure to assess the emissions is different.

LX/SX/EW has the highest GWP comparing both hydro- and pyro-processes. This is attributed to the fact that many process-steps are grouped in LX/SX/EW (see **Table 3**). In particular, EW is expected to have a high power demand and therefore its related emissions.

This study does not allow a high *process-step resolution* (the number of substeps involved in every represented stage) view of the processes, especially for hydro-process. This fact is restricting the analysis since the higher *process-step resolution* a study has the better understanding of the process and its emissions the study can achieve. In spite of that, notice that the overall results shouldn't change significantly when improving *process-step resolution* since the most relevant energy flows have been already identified. Also notice that improving this feature of the study will allow to identify new opportunities to integrate solar technologies.

In order to improve *process-step resolution* it is necessary to represent the processes with more detail. Improving this feature, along with achieving a better description of energetic resources' purpose in the process, will also allow to understand the energy issues related to water and services processes. To do this, more information is needed. But the more detail is used to represent the processes the less representativeness of the overall industry the model will provide. At a certain level of detail (or *process step-resolution*) specific case studies are going to be needed. This appears as a natural next stage for this research. A survey to obtain data from mining companies was designed as presented in **Appendix 5: Data collection survey**.

The process stage with the highest fossil fuel related emissions per ton of copper is open pit mining. This fact can be explained by the high amounts of diesel required to transport the mineral by trucks [15].

Alternatives for diesel transport-applications are not evaluated in this study. Biofuels, which come from a biological transformation of solar energy, can be an alternative to diesel in transportation processes. They could be also used to power other machines with internal combustion engines. Technical and legal viability of these options should be analyzed before assessing its environmental impacts. The evaluation of these alternatives is proposed as a future step in the SolarMining project. Additionally, if the use of the energy demanded is known other technologies could be assessed to satisfy those necessities in next stages of this research.

3.2. Solar technology integration scenarios

Figure 18 represents the scenarios simulated in this study. The selection of the scenarios is explained in **section 1**. Results are presented in this section.

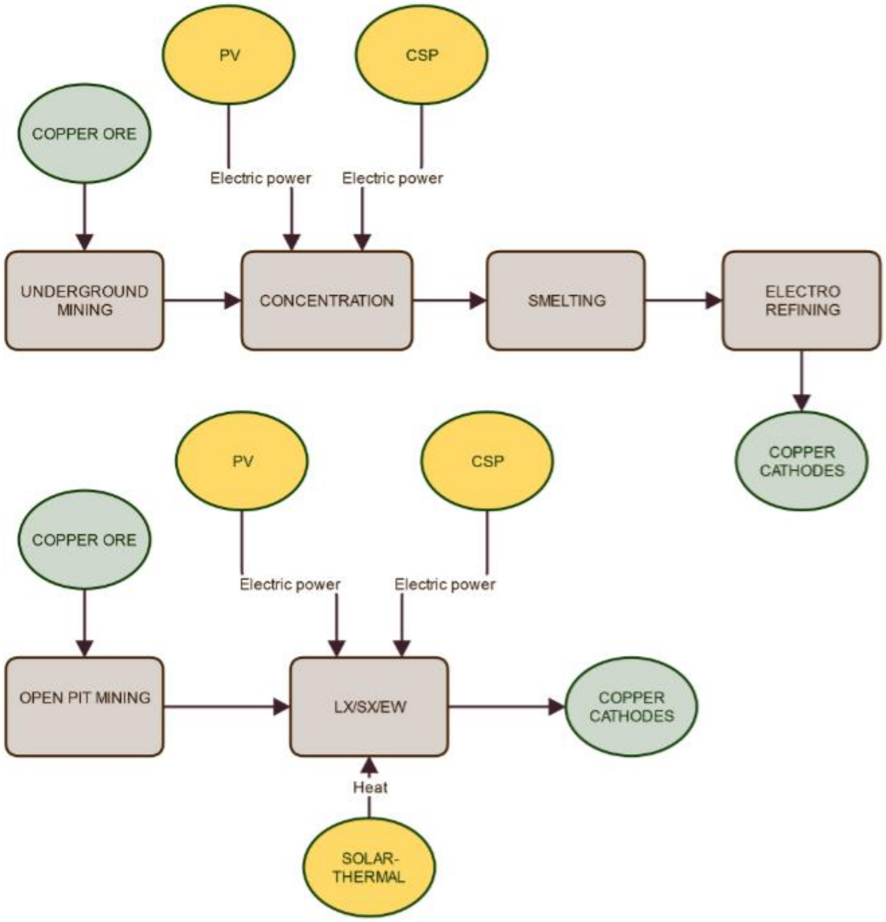
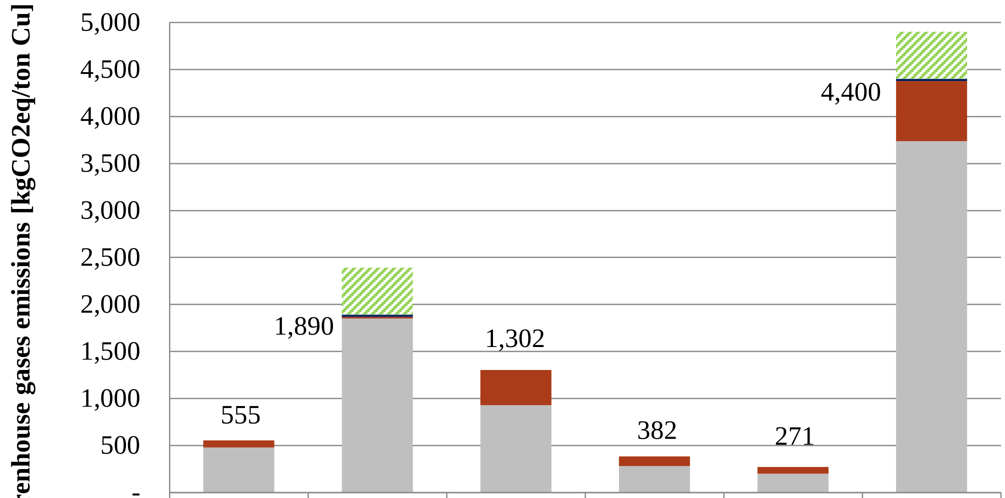


Figure 18: Solar technologies integration map

3.2.1. PHOTOVOLTAIC ELECTRIC GENERATION INTEGRATION

Figure 19 and **Figure 20** show the estimated impacts in GWP of suppling 22% of electric energy demanded in concentration and LX/SX/EW stages of pyro- and hydro-processes with PV technology.



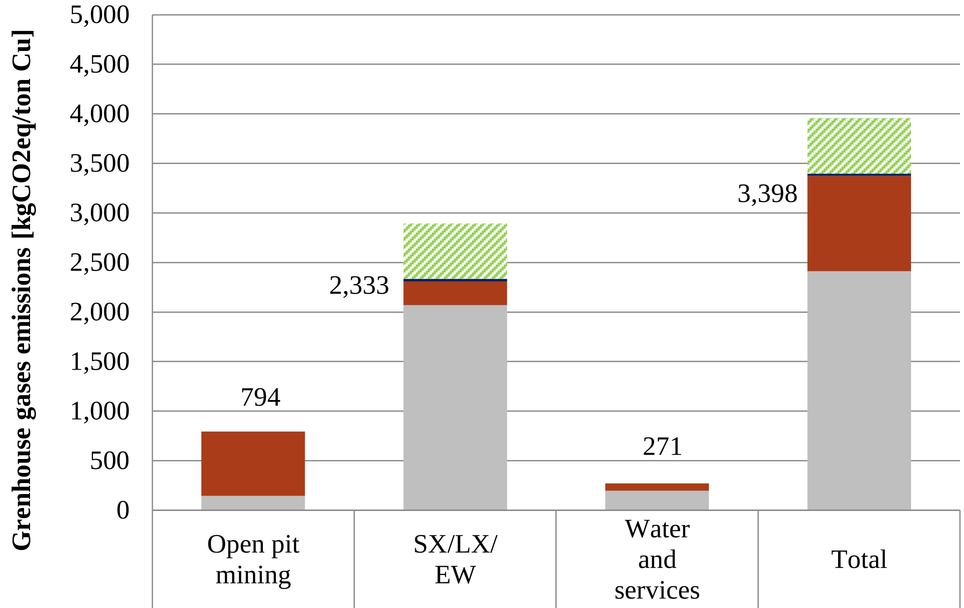
	Under-ground mining	Concen-tration	Smelting	Electro refining	Water and services	Total
Saved GHG emissions [kgCO2eq/ton Cu]		501				501
Solar plant related emissions [kgCO2eq/tonCu]		21				21
Fossil fuels related emissions [kgCO2eq/ton Cu]	77	17	374	101	73	643
Electricity related emissions [kgCO2eq/ton Cu]	478	1,852	928	281	198	3,736

Figure 19: GWP of pyrometallurgical process for PV integration scenario. Prepared with GaBi model results.

In pyro-process 501 [kgCO_{2eq}(ton Cu)$^{-1}$] of GHG emissions are saved when supplying 22% of the electric energy demanded by concentration stage with PV technology. This savings make pyro-process GWP decrease in 10%.

On the other hand hydro-process saves 561 [kgCO_{2eq}(ton Cu)$^{-1}$] when supplying 22% of the electric energy demanded by LX/SX/EW with PV. This represents savings of 14% in the whole process emissions.

PV plant construction emissions (allocated by energy yield during whole life span) are estimated at 21 [kgCO_{2eq}(ton Cu)$^{-1}$] and 24 [kgCO_{2eq}(ton Cu)$^{-1}$] for pyro- and hydro-processes. The size of the plants has been estimated with northern Chile solar irradiance levels. But for PV plants construction the emissions arising from transportation processes has not been adapted to Chilean conditions. Improving construction related emissions for PV plants estimations is proposed for future investigation. But its low relative contribution to overall-process emissions estimated in this study should be considered when assigning priorities. With this in mind, its priority should be low.



	Open pit mining	SX/LX/ EW	Water and services	Total
Saved emissions [kgCO2eq/ton Cu]		561		561
Solar plant related emissions [kgCO2eq/tonCu]		24		24
Fossil fuels related emissions [kgCO2eq/ton Cu]	649	239	73	961
Electricity related emissions [kgCO2eq/ton Cu]	145	2,070	198	2,413

Figure 20: GWP of hydrometallurgical process for PV integration scenario. Prepared with GaBi model results.

To have a first impression on the feasibility of supplying this amount of solar energy a rough estimation of its size is performed. Accordingly, a certain production level must be selected. Just as an example CODELCO division Gabriela Mistral is selected. This division produced 121.012 tonnes of electrowon copper (via pyro-process) [29]. Also *Ecoinvent* data base report about PV technologies informs an average area of $7.58x10^{-3}[m^2/W]$ [23]. According to industry's average data used in this study in order to supply 22% of LX/SX/EW stage electric demand 351,293 $[m^2]$ of PV power plant are required (a 46 [MW] plant). This area is equivalent to approximately 33 soccer fields. There are in Chile PV plants with capacities above 46 [MW] such as *Amanecer Solar* a 100 [MW] plant owned by CAP mining company [30].

The above mentioned comparisons suggest technical feasibility of the implementation of the technology evaluated in this section. But, still an economic evaluation is critical when deciding its implementation. Economic assessments are not part of this study but are a necessary step to design strategies to integrate more solar technologies in the Chilean mining industry and reduce its emissions.

Emission savings estimations were presented in this section. These savings are not directly attributable to a mining company which eventually implements one of the evaluated alternatives.

Given that the proposed plants would have to be connected to the SING and the mining operations would continue taking their energy from this system the new emissions attributable to the companies should be calculated using the new SING emission factor (after solar plant connection).

In PV alternatives, and every other alternative evaluated in this study, solar technologies have been coupled with a specific process stage. This, despite the electricity generated with solar technologies can be used to supply any stage. The aim of this decision is to start thinking of mining operation-solar technology interactions beyond a simple replacement of energy sources but as processes that can be designed and operated to work coupled. Efforts in this direction are being carried out in the context of SolarMining project and are proposed as a future step in this investigation.

Sensitivity analysis were performed for PV integration in both pyro- and hydro-processes. Its results are summarized in **Figure 21** and **Figure 22**.

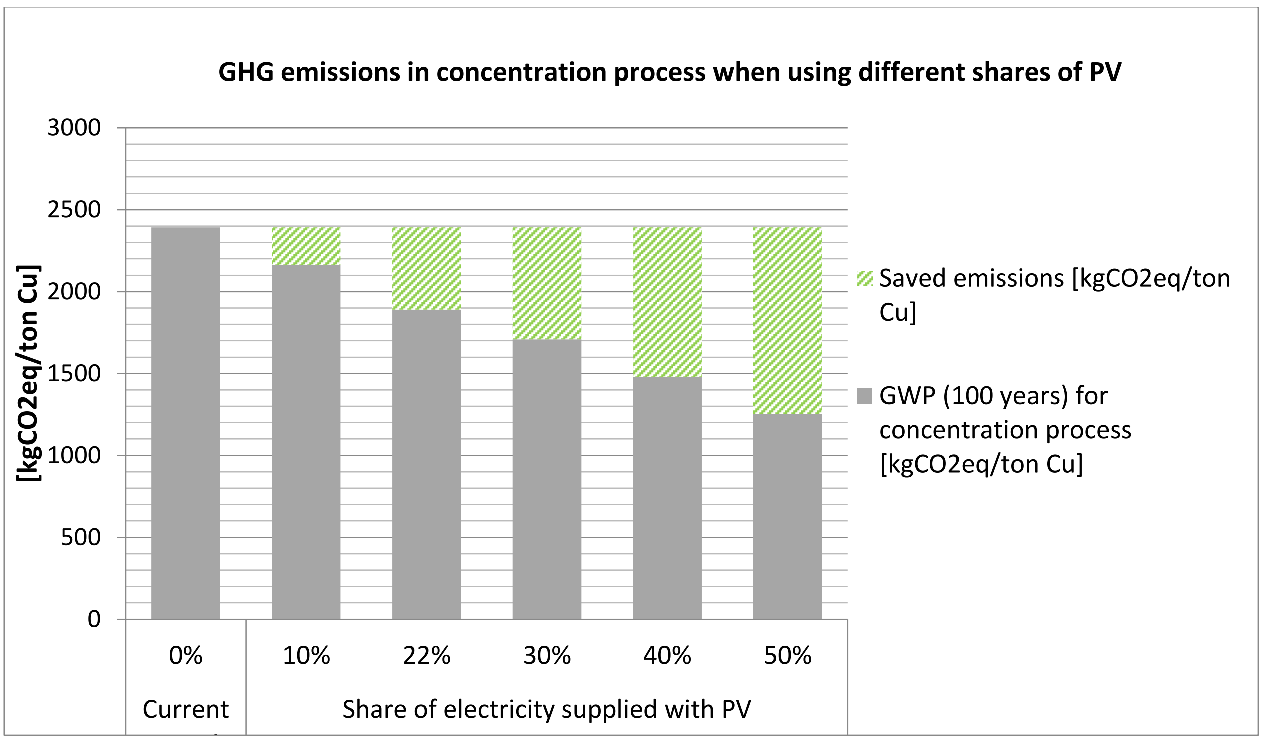


Figure 21: Sensitivity analysis for PV integration in concentration. Prepared with GaBi model results.

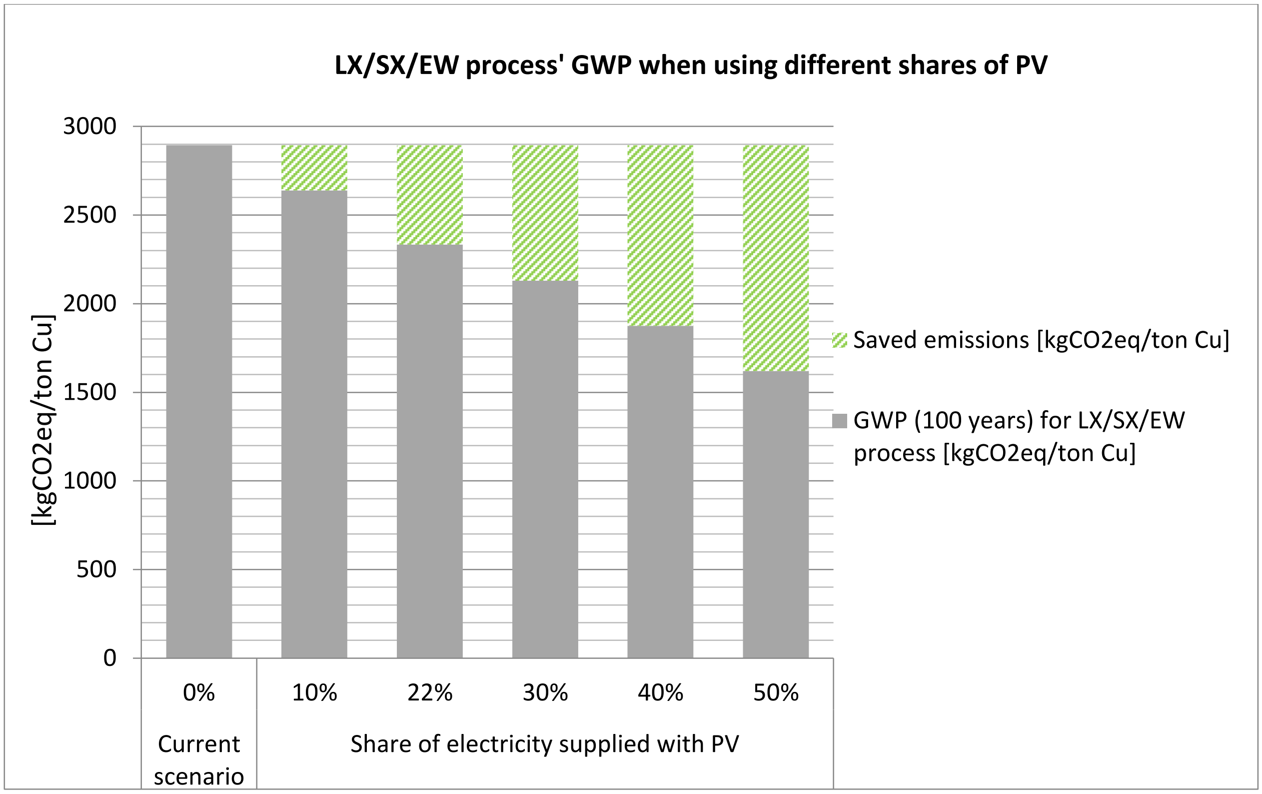


Figure 22: Sensitivity analysis for PV integration in LX/SX/EW. Prepared with GaBi model results.

As expected the more energy is supplied with PV the more GHG emissions are saved. In both processes a linear behavior is observed when varying share of electricity supplied with PV. This fact is explained by the characteristics of the employed models.

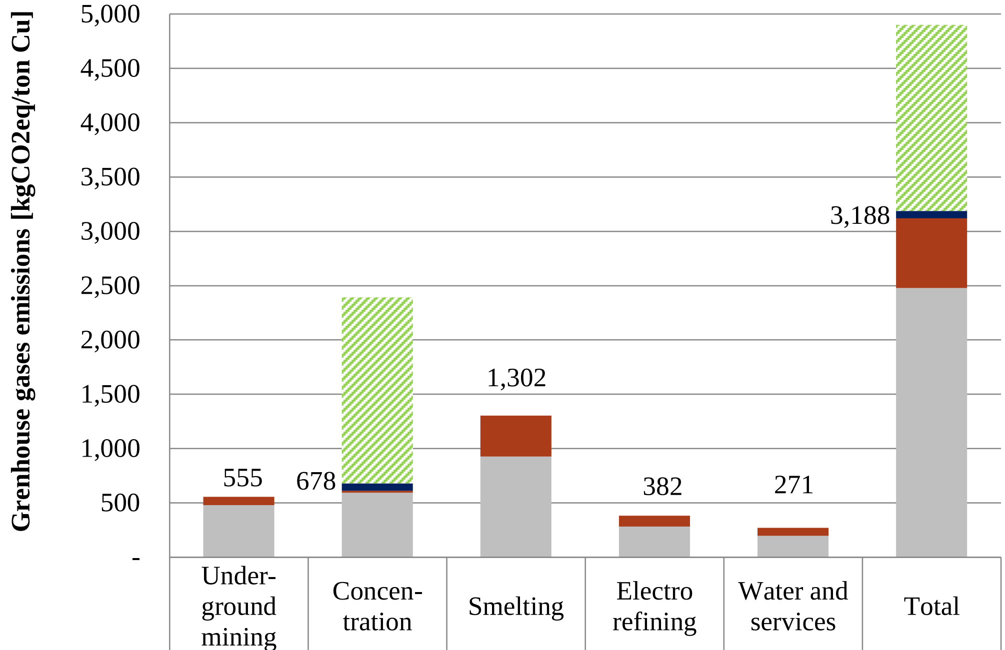
Despite looking at **Figure 21** and **Figure 22** it could seem that the better alternative is to use as much PV as possible there are both technical and economic considerations on this issue. Proposed alternatives need to be sustainable also from an economic point of view. Technical issues regarding solar resource availability (irradiance level variation) and therefore system stability have to be studied and are proposed for future steps of this investigation. Those analysis have not been included in this study.

Northern Chile's ISO (called *Centro económico de despacho de carga* CDEC-SING) is in charge of coordinating northern Chile's electric system operation. From modelling perspective, system stability issues (arising, for example, from variations in power yield of PV plants) can be driven if including CDEC-SING algorithms in the analysis.

On the other hand, from the perspective of the technological alternatives, low-emissions technologies improving system flexibility need to be assessed. An example of these technologies is presented in next section where CSP with storage technology is evaluated.

3.2.2. *Concentrated solar power (CSP) electric generation integration*

Figure 23 and **Figure 24** show the estimated impacts in GWP of suppling 75% of electric energy demanded in concentration and LX/SX/EW stages of pyro- and hydro-processes, respectively, with CSP technology.

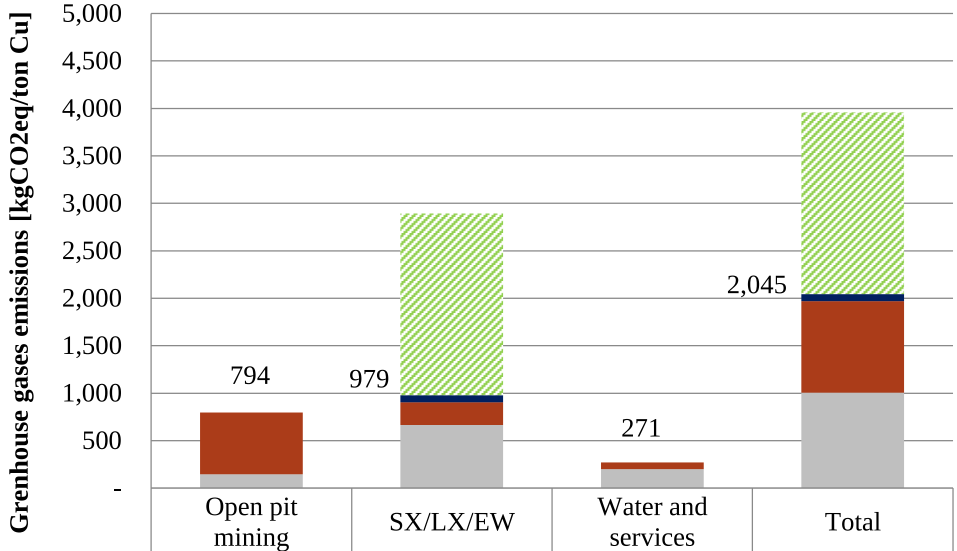


	Under-ground mining	Concen-tration	Smelting	Electro refining	Water and services	Total
Saved GHG emissions [kgCO2eq/ton Cu]		1,713				1,713
Solar plant related emissions [kgCO2eq/tonCu]		68				68
Fossil fuels related emissions [kgCO2eq/ton Cu]	77	17	374	101	73	643
Electricity related emissions [kgCO2eq/ton Cu]	478	594	928	281	198	2,478

Figure 23: GWP of pyrometallurgical process for CSP integration scenario. Prepared with GaBi model results.

In pyro-process 1,713 [kgCO_{2eq}(ton Cu)$^{-1}$] of GHG emissions are saved when supplying 75% of the electric energy demanded by concentration stage with CSP technology. This savings make pyro-process GWP decrease in 35%.

On the other hand hydro-process saves 1,915 [kgCO_{2eq}(ton Cu)$^{-1}$] when supplying 75% of the electric energy demanded by LX/SX/EW with CSP. This represent savings of 48% in the whole process emissions.



	Open pit mining	SX/LX/EW	Water and services	Total
Saved emissions [kgCO2eq/ton Cu]		1,915		1,915
Solar plant related emissions [kgCO2eq/tonCu]		76		76
Fossil fuels related emissions [kgCO2eq/ton Cu]	650	240	73	963
Electricity related emissions [kgCO2eq/ton Cu]	145	664	198	1,006

Figure 24: GWP of hydrometallurgical process for CSP integration scenario. Prepared with GaBi model results

The emissions for CSP electric generation are estimated by Telsnig in 30 [$gCO_{2eq}(kWh_{el})^{-1}$] [24]. These emissions are due to construction phase of a CSP project and are allocated by its estimated generation for its whole life span. They are calculated with Telsnig's model for CSP plants, are adapted to Chilean context and distance dependent variables are referred to Calama. This location could be varied in the future and the GHG released to the atmosphere can be re-calculated with Telsnig's model.

However, CSP plant construction-related GHG emissions (solar plant-related emissions) are low when compared to emissions related to the power taken from SING. For instance in CSP integration in pyro-process scenario, where construction-related emission are estimated at only 68 [$kgCO_{2eq}(ton\ Cu)^{-1}$], electricity-related emissions are 594 [$kgCO_{2eq}(ton\ Cu)^{-1}$].

This study evaluates only environmental issues of these alternatives. Technical and economic evaluations need to be performed in the future. These assessments can also help defining optimal configurations for important features of the system such as specific technologies to use and storage size. Stability should be considered as a technical advantage of this alternative when compared to other alternatives such as photo-voltaic.

From a technical perspective, the feasibility of the implementation of this technology is supported by the existence of CSP projects in the north of Chile. For example 10 [MW_{th}] *El Tesoro* solar-thermal plant with parabolic trough technology (operative) [24] and 400 [MW] *María Elena* with tower technology (announced and with favorable environmental qualification resolution RCA) [31].

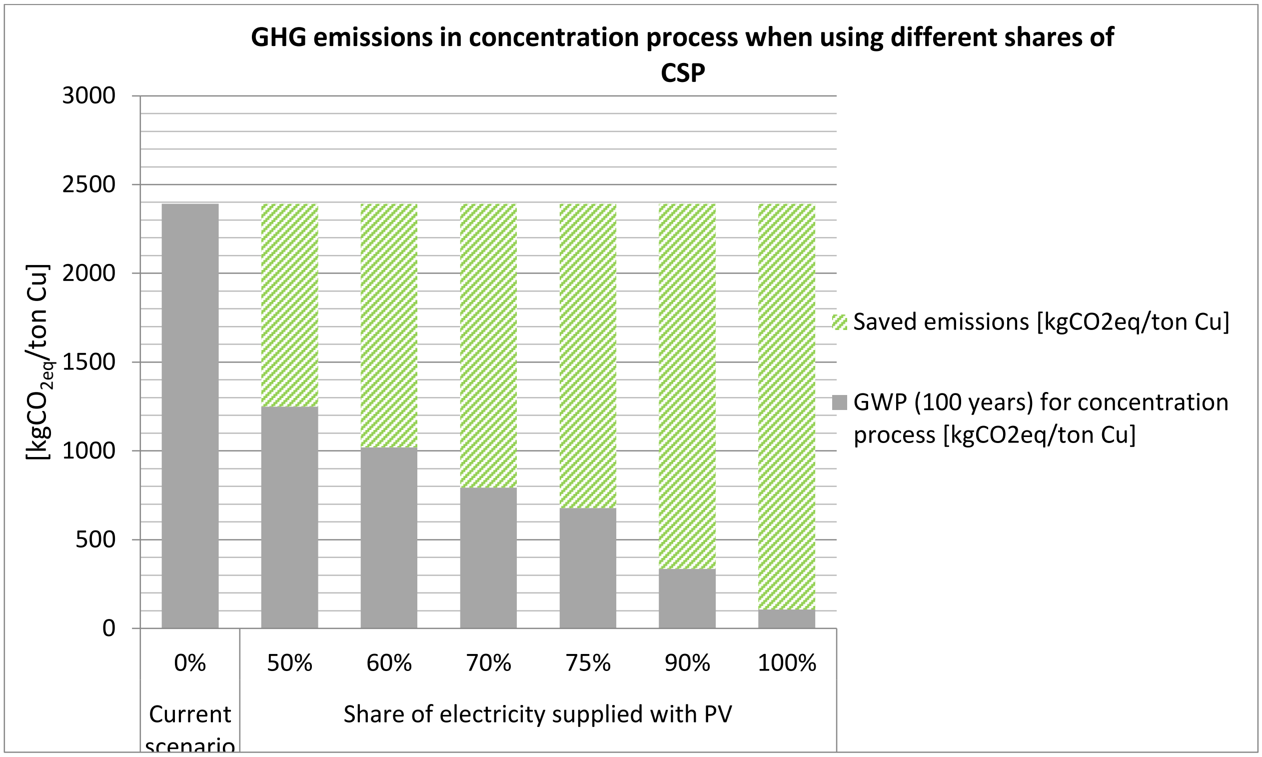


Figure 25: Sensitivity analysis for CSP integration in concentration. Prepared with GaBi model results

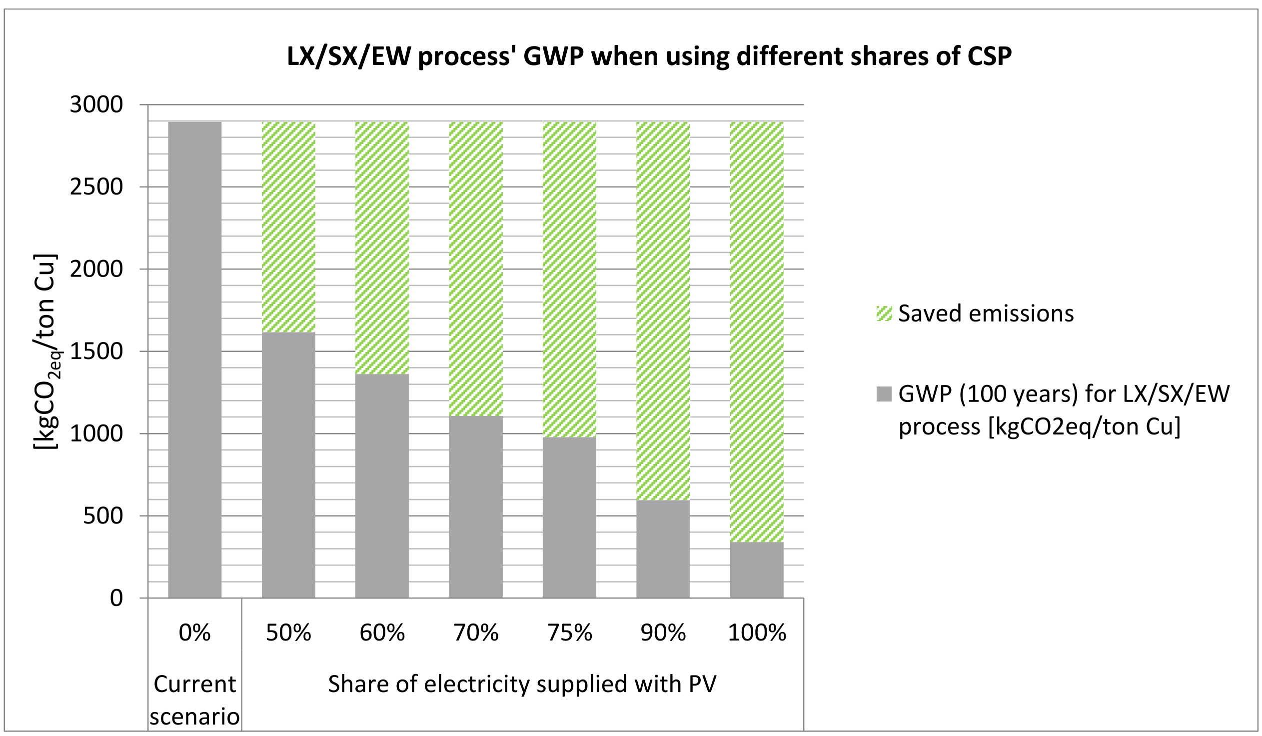


Figure 26: Sensitivity analysis for CSP integration in LX/SX/EW. Prepared with GaBi model results

In both processes a linear behavior is observed when varying share of electricity supplied with CSP. This fact is explained by the characteristics of the employed models, since linear balances were used to represent the outputs (emissions) as a function of the inputs (energy from a certain source).

As expected the more energy is supplied with CSP the bigger reduction on pyro- and hydro-processes GWP is achieved. For example when supplying 100% of electricity for LX/SX/EW with CSP, hydro-process GWP decreases by 65%.

As mentioned before this alternative includes storage technology. This feature allows it to supply a larger portion of the demanded energy. But in spite of the environmental benefit of a larger share of CSP shown in **Figure 25** and **Figure 26** there can be technical and economic limitations. Nevertheless, in this first approach CSP alternative shows a bigger GWP reduction potential than PV, thus its analysis should be a priority. An economic evaluation of this alternative needs to be conducted in the next steps of this research.

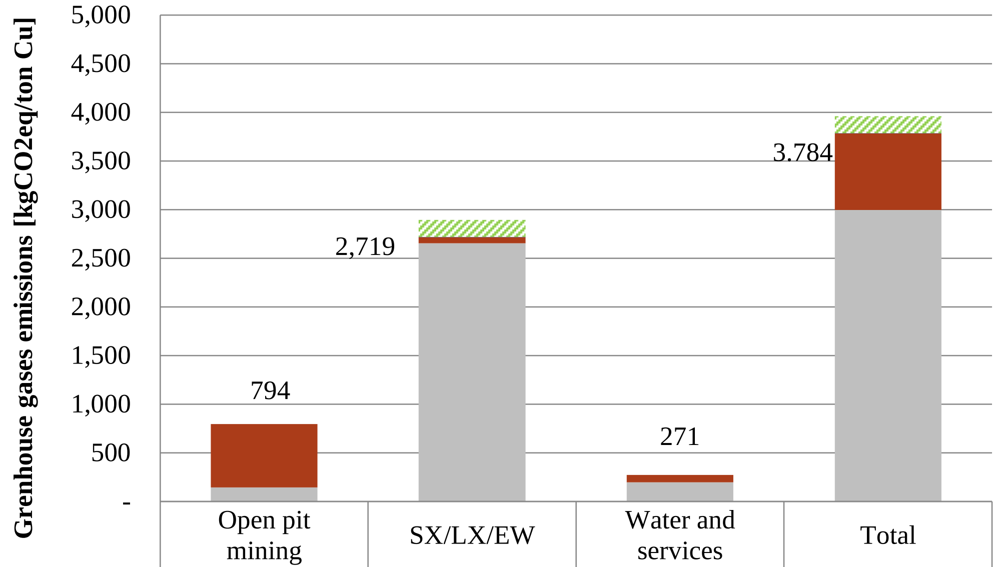
3.2.3. Solar thermal heat generation integration

The last technology evaluated in this study is solar thermal heat generation employing flat plate collectors. Its use was evaluated as a replacement of diesel for electrolyte heating. The impacts of replacing 85% of LX/SX/EW diesel consumption are represented in **Figure 27**.

Hydro-process GWP decreases by 175 [$kgCO_{2eq}(ton\ Cu)^{-1}$] with the implementation of this alternative. It means overall GWP will decrease 4%.

Solar thermal shows the lowest saved emissions of every assessed option. This is explained by the low participation of fossil fuels versus electricity generation in total emissions.

Solar thermal flat plant construction emissions (allocated by energy yield during whole life span) are estimated at 3 [$kgCO_{2eq}(ton\ Cu)^{-1}$]. These emissions are estimated using *Ecoinvent* data. The size of the plant has been estimated with northern Chile solar irradiance levels. But emissions arising from transportation processes have not been adapted to Chilean conditions. Improving estimation of construction related emissions for solar thermal plants is suggested as a future task.



	Open pit mining	SX/LX/EW	Water and services	Total
Saved emissions [kgCO2eq/ton Cu]		175		175
Solar plant related emissions [kgCO2eq/tonCu]		3		3
Fossil fuels related emissions [kgCO2eq/ton Cu]	650	62	73	785
Electricity related emissions [kgCO2eq/ton Cu]	145	2,654	198	2,997

Figure 27: Hydrometallurgical process' emissions for flat plate solar heat integration scenario. Prepared with GaBi model results

As mentioned in **section 2** the share of diesel replaced by solar thermal plant is taken from an operative example of the application of this technology: Pampa Elvira Solar [28]. The existence of this plant shows the technical feasibility of this alternative.

This alternative is interesting because it has a different approach from CSP and PV. First it assesses a different type of energy. But more important is the fact that the configuration of this alternative was possible because there is information about what is the energetic resource being used for in the mining process.

For both PV and CSP alternatives it was only considered that processes have a certain electric energy demand but it was not taken into account its purpose. When the applications of the demanded energetic supplies are known a broader spectrum of alternatives can be analyzed in the search for a cleaner industry. This approach to explore alternatives is going to be referred as *process-comprehensive approach*. This fact was taken into account when designing the survey to get data from mining companies for future steps of this investigation (presented in **Appendix 5: Data collection survey**).

A sensitivity analysis was also performed for this scenario. **Figure 28** shows the effects in hydro-process' GWP when varying solar heat share of diesel substituted.

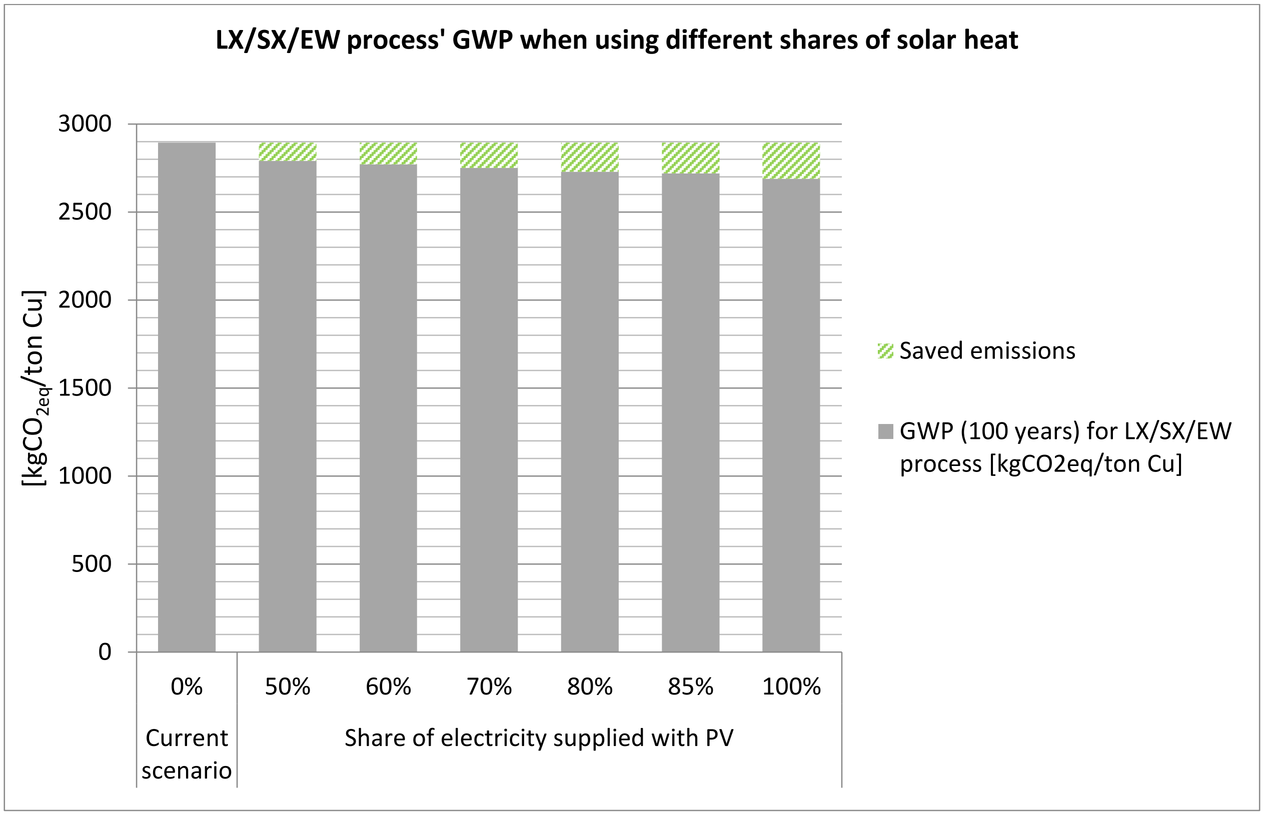


Figure 28: Sensitivity analysis for solar thermal integration in LX/SX/EW. Prepared with GaBi model results

As can be seen in **Figure 28** even when replacing 100% of LX/SX/EW diesel demand the impact of this alternative is low. In that case 206 [$kgCO_{2eq}(ton\ Cu)^{-1}$] are saved representing a 5% decrease in whole process emissions. This is again explained by the low participation of diesel related emissions when compared to electricity related emissions for the whole hydro-process.

A linear behavior is observed when varying share of diesel replaced by solar thermal energy. Again, this fact is explained by the characteristics of the employed models.

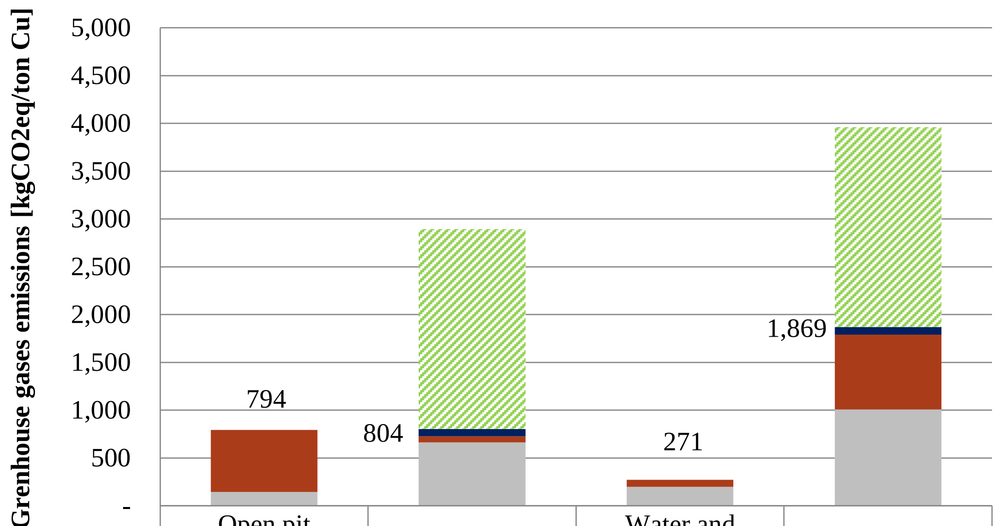
An interesting feature of this alternative is that the GHG emissions savings can be directly attributed to mining companies which implement it. Because this alternative directly replaces the consumption of fossil fuels and its related combustion emissions.

In order to decide the optimal share of participation for this technology in the process both technical and economic evaluations are required. This evaluations should be performed in next steps of this investigation.

It is important when carrying out technical and economic evaluation of this alternative to consider the effects it has in the performance of the mining process. This given that the requirements of the process are being directly satisfy with a different technology. This consideration is especially relevant when looking for new alternatives from a *process-comprehensive approach.* The process performance could be either improved or impaired. For example, more stability in the temperature of the electrolyte could be achieved and therefore better quality cathodes could be produced. Other example is the speed in reacting if a change in the temperature is required, this speed could be either improved or impaired. These and other implications should be carefully analyzed in future steps.

3.2.4. Combined technologies scenario

In this scenario two solar technologies supplying a process at the same time are assessed. **Figure 29** shows the impact on hydro-process' GWP of replacing 85% of LX/SX/EW diesel consumption with solar thermal heat generation and supplying 75% of LX/SX/EW electricity demand with CSP.



	Open pit mining	SX/LX/EW	Water and services	Total
Saved emissions [kgCO2eq/ton Cu]		2,090		2,090
Solar plant related emissions [kgCO2eq/tonCu]		78		78
Fossil fuels related emissions [kgCO2eq/ton Cu]	650	62	73	785
Electricity related emissions [kgCO2eq/ton Cu]	145	664	198	1,006

Figure 29: Hydrometallurgical process' emissions for CSP and flat plate solar heat integration scenario. Prepared with GaBi model results

2.090 [$kgCO_{2eq}(ton\ Cu)^{-1}$] are saved when implementing this alternative. It means hydro-process' GWP decreases by 53%.

In addition to its high GHG emissions saving potential, this alternative is interesting since it combines two different solar technologies. This assessment shows that combination of technologies can maximize environmental benefit. In future steps of this investigation and SolarMining project different alternatives can be assessed at the same time so an optimal mix of solar technologies for a given process can be determined.

The search for an optimal mix of technologies can be enriched by adopting a *process-comprehensive approach.*

3.3. Final commentaries

Table 5 summarizes the results obtained for every simulated scenario.

Table 5: Simulated scenarios results summary

Scenario	Copper process	Stage supplied	% supplied with solar technology	Process original emissions [$kgCO_{2eq}$ (ton Cu)$^{-1}$]	Emissions saved [$kgCO_{2eq}$ (ton Cu)-1]	GWP reduction in overall process
PV electric generation integration	Pyro-	Concentra-tion	22% of electric demand	4,901	501	10%
	Hydro-	LX/SX/EW	22% of electric demand	3,960	561	14%
CSP electric generation integration	Pyro-	Concentra-tion	75% of electric demand	4,901	1,713	35%
	Hydro-	LX/SX/EW	75% of electric demand	3,960	1,915	48%
Solar-thermal heat generation integration	Hydro-	LX/SX/EW	85% of diesel demand	3,960	175	4%
Combined scenario (CSP and solar-thermal)	Hydro-	LX/SX/EW	75% of electric demand and 85% of diesel demand	3,960	2,090	53%

As shown in **Table 5** the biggest GWP savings are achieved when simulating CSP technology integration. Thus, this technology would be more interesting when analyzing alternatives to reduce GWP. Also, as pointed out before, including different solar technologies in order to allow a bigger share of solar energy in the mining processes, implies even bigger reductions in GWP.

In this study emissions have been estimated per tonne of copper produced so no attention has been paid to production levels of pyro- and hydro-processes. This is relevant since it conditions the impact that the eventual implementation of proposed alternatives can have on overall industry emissions.

For example during 2014 LX/SX/EW stage processed 1,844,000 tonnes of copper while concentration stage processed 3,905,600. Therefore the potential impact of a wide spread application of a cleaner alternative in the latter is higher.

Finally, it is important to consider that an environmental impact assessment has done in this study and technical and economic evaluations have been either discussed or proposed. But is also relevant when proposing new alternatives for the industry to evaluate its social impacts. This type of evaluations should be performed in later steps of the SolarMining project.

4. Conclusions and Recommendations

A LCA focused on GWP was conducted and a first approach to current Chilean copper mining industry emissions was obtained. GWP for average Chilean copper pyrometallurgical process was estimated at 4,901 [$kgCO_{2eq}(ton\ Cu)^{-1}$] while for hydrometallurgical process was estimated at 3,960 [$kgCO_{2eq}(ton\ Cu)^{-1}$].

In both pyro- and hydro-process most of the GHG emissions are electricity-related. 87% of pyro-process' GWP is due to electricity generation in system's power plants and 76% in hydro-process. Thus, the recommendation is that evaluation of cleaner technologies for electricity generation should be a priority when trying to reduce copper industry's GHG emissions.

Concentration and LX/SX/EW stages contributes with the highest GHG emissions in their respective processes and open pit mining is the process step with highest fossil fuel related emissions. So these stages should concentrate the efforts to find cleaner solutions.

But notice that in order to identify new opportunities to integrate solar technologies, *process step-resolution* in the model and information about energy resources purpose in the process need to be improved in future stages of this work. To do this, specific case studies will be required. Having access to less aggregated data from COCHILCO is useful to both improve *process step-resolution* and keep the results in a general level. Data access is a key issue when performing a LCA study.

Results for current scenario GWP of mining processes in Chile have similar magnitude with data found in literature for this type of processes. When analyzing other LCA studies the importance of reporting every assumption is noted. Thus, a very transparent communication of the modeling, data sources and assumptions is recommended when publishing results. It is also recommended to pay special attention to pyro-process GWP estimation when refining the results. This, minding that the estimation from this study is bigger than the others used to compare.

The environmental consequences in terms of GWP of the integration of selected solar technologies was estimated using the developed LCA model. The results show that solar energy allows to reduce mining processes' GWP. The highest GWP reduction is achieved when both CSP and solar thermal technologies are integrated in hydro-process. 2,090 [$kgCO_{2eq}(ton\ Cu)^{-1}$] are saved and GWP of this process decreases 53%. Also, when only replacing electric power sources, the highest GWP savings are produced when using CSP. Then, form a purely global warming-impact perspective, mixed alternatives and CSP are the most interesting for future analysis. Also, CSP technology has the structural advantage of having a bigger capacity factor since it has an *included* storage system.

Construction related emissions for PV plants estimations could be improved in future steps of the investigation. But its contribution to overall emission is not high so it shouldn't be a priority.

Emissions savings adjudication to mining companies have to be carefully deal with when these are due to electric generation and the plants are connected to the system.

Sensitivity analysis of solar technologies participation show linear decreasing of GWP with solar share increase (due to the model used to represent the interactions). Solar technologies participation may be bounded by technical or economic reasons. Both type of analysis (technical and economic) are recommended to be performed in the next stages of the research. But it should be noticed that technical feasibility of the implementation of the selected types of solar technologies is supported by the presence of these type of plants in Chile.

A *process-comprehensive approach* is suggested for future analysis in order to consider a broader spectrum of alternatives in the study. It is also important to achieve a better understanding of water and services-related energy demand. Evaluation of alternatives including a mix of technologies is also suggested.

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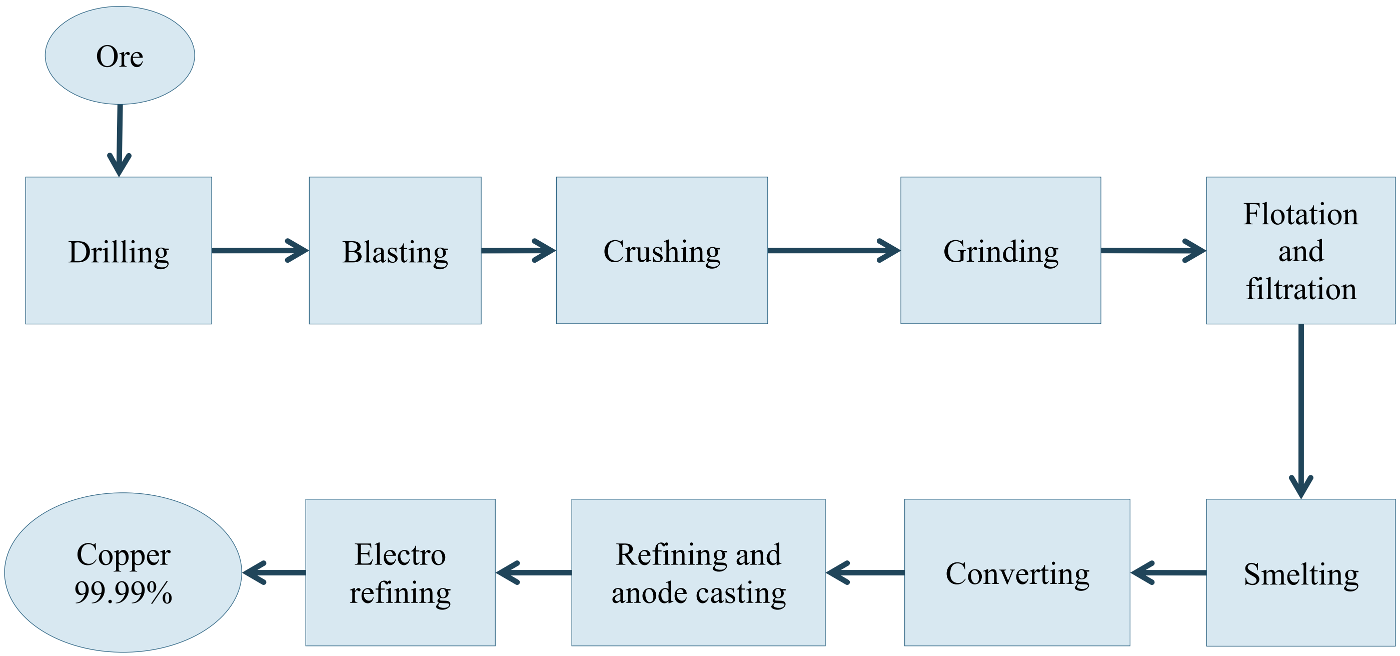
6. APPENDIXES

6.1. APPENDIX 1: COPPER PROCESSES DESCRIPTION

Block diagrams and descriptions based on the information presented in [14].

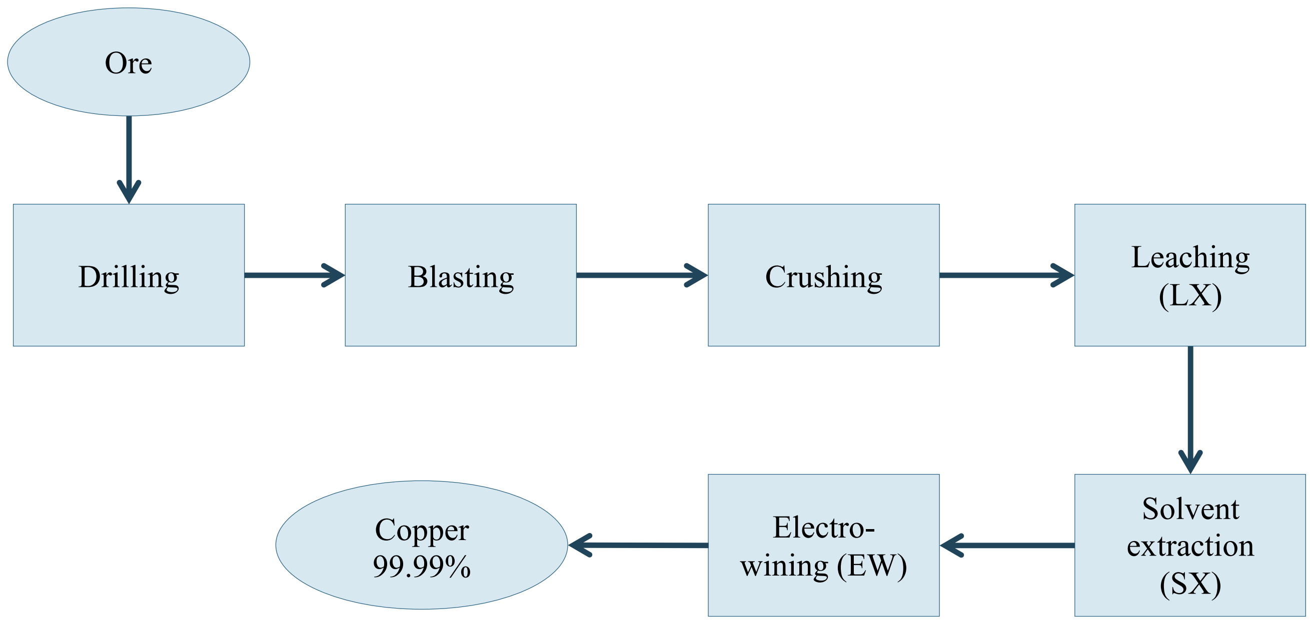
6.1.1. PYROMETALLURGICAL PROCESS



Copper mineral is first mined from the ground using drilling and blasting techniques. It can be done both in open pit or underground mining types of mines. Then the size of the material needs to be reduced. A series of comminution processes if performed. Usually a primary crushing stage is performed at the mining site and then a secondary crushing process is done. After this successive grinding stages take place. When the mineral has the proper size it is taken to a concentration process. Here, forth flotation operation is used to separate the particles containing copper. Then it is necessary to remove the water. Most common operations to do this include settling and filtration. The material resulting from these processes is called copper concentrate and typically contains between 20% and 30% of copper.

Before starting the smelting process a drying operation can be used, which allows to reduce the water content and improve the efficiency of the smelting process. Then, the concentrate is fed into a reactor to be smelted and produce copper matte, which contains around 50% - 70% of copper. After this, the matte is oxidized in the converting process to produce impure molten copper. Then, the impure molten copper is refined in a final reactor, then it is casted to be taken to the electro-refining process where high purity copper is produced.

6.1.2. HYDROMETALLURGICAL PROCESS



As in pyro-process, copper mineral obviously needs to be mined from the ore. Again, it is done by drilling and blasting. This time the mineral size is also going to be reduced but the final size is going to be bigger compared to pyro-process requirements. Then, copper is recovered from the rocks by leaching (LX) process, which consist on using sulfuric acid to transfer copper ions from the rock to the liquid solution of water and sulfuric acid. After this, the concentration of the solution is increased via solvent extraction (SX), which consist on the use of an organic compound to transfer the copper ions from de leaching solution to a high concentration copper electrolyte. Finally the copper is recovered from the electrolyte by electro-wining and high purity copper cathodes are produced.

6.2. Appendix 2: Fossil fuel shares estimations

The fossil fuel mix is assumed to be composed by diesel, natural gas and heavy fuel oil. For every process stage diesel input is known from [16]. The rest of the fossil fuel supply is assumed as a mix of natural gas and heavy fuel oil in a 6:8 proportion.

6.3. Appendix 3: PV yield under northern Chile irradiance conditions

6.3.1. PV for concentration

Total electric energy used in concentration process (with copper production data from [22]):

$$\mathrm{E_{dem}} = 3{,}905.6 \cdot 1{,}000\ [\mathrm{tonCu}] \cdot 10810 \left[\frac{MJ}{tonCu}\right] = 4.22 \cdot 10^{10} [\mathrm{MJ}]$$

Power demanded:

$$\mathrm{P} = \frac{\mathrm{E_{dem}}}{31{,}557{,}600 \left[\frac{s}{year}\right]} = 1.34 \cdot 10^{3} [\mathrm{MW}_e] \rightarrow \text{design power for PV plant}$$

To estimate PV plant yield in northern Chile conditions average yield for PV plants in Switzerland (chosen because of data availability) documented in *Ecoinvent* report [23] was employed. PV plants in Switzerland have an average yield of 820 [kW_h/kW_p] per year and an average global horizontal solar irradiation of 1.100 [kW_h/m^2] per year.

From *explorador solar* database [26] for solar irradiance Calama's the potential yield for 2014 was obtained: 2608,28 [kW_h/m^2] per year.

Then the yield (per year) of a PV plant located in northern Chile is estimated as follows:

$$yield = \frac{2{,}608 \left[\frac{kW_h}{m^2}\right] \cdot 820 \left[\frac{kW_h}{kW_p}\right]}{1{,}100 \left[\frac{kW_h}{m^2}\right]} = 1{,}944 \left[\frac{kW_h}{kW_p}\right]$$

Then, generated energy (per year):

$$\mathrm{E_{gen}} = 1{,}944 \left[\frac{\mathrm{kW_h}}{\mathrm{kW_p}}\right] \cdot \mathrm{P}$$

$$\mathrm{E_{gen}} = 1{,}944 \left[\frac{\mathrm{kW_h}}{\mathrm{kW_p}}\right] \cdot 1.34 \cdot 10^{6} [\mathrm{kW_p}] = 26.05 \cdot 10^{8} [\mathrm{kW_h}] = 9.38 \cdot 10^{9} [\mathrm{MJ}]$$

Energy supplied by PV (%):

$$\mathrm{PV_{supply}} = \frac{\mathrm{E_{gen}}}{\mathrm{E_{dem}}} = 21.75\% \quad \rightarrow \quad 22\%$$

*6.3.2. PV FOR LX/*SX/EW

Total electric energy used in LX/SX/EW process (with copper production data from [22]):

$$\mathrm{E_{dem}} = 1{,}844 \cdot 1{,}000[\mathrm{tonCu}] \cdot 12{,}085.8 \left[\frac{MJ}{tonCu}\right] = 2.23 \cdot 10^{10}[\mathrm{MJ}]$$

Power demanded:

$$\mathrm{P} = \frac{\mathrm{E_{dem}}}{31557600 \left[\frac{\mathrm{s}}{\mathrm{a}}\right]} = 706{,}64[\mathrm{MW}] \rightarrow \text{design power for PV plant } [\mathrm{MW_p}]$$

$$\mathrm{E_{gen}} = 1944 \left[\frac{\mathrm{kW_h}}{\mathrm{kW_p}}\right] \cdot 706.64 \cdot 10^3 [\mathrm{kW_p}] = 1{,}37 \cdot 10^9 [\mathrm{kW_h}] = 4{,}93 \cdot 10^9 [\mathrm{MJ}]$$

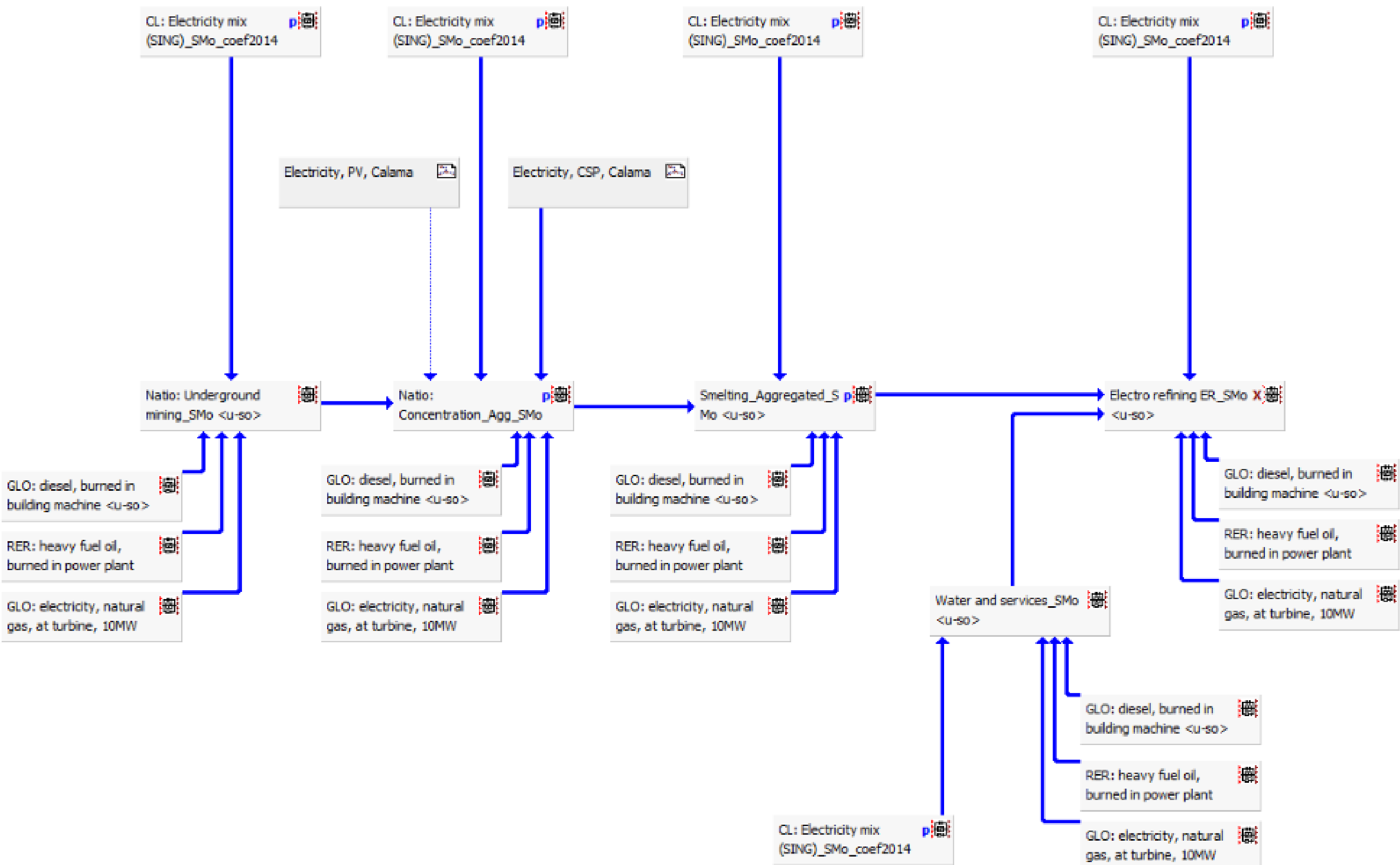
Energy supplied by PV (%):

$$\mathrm{PV_{supply}} = \frac{\mathrm{E_{gen}}}{\mathrm{E_{dem}}} = 22.11\% \quad \rightarrow \quad 22\%$$

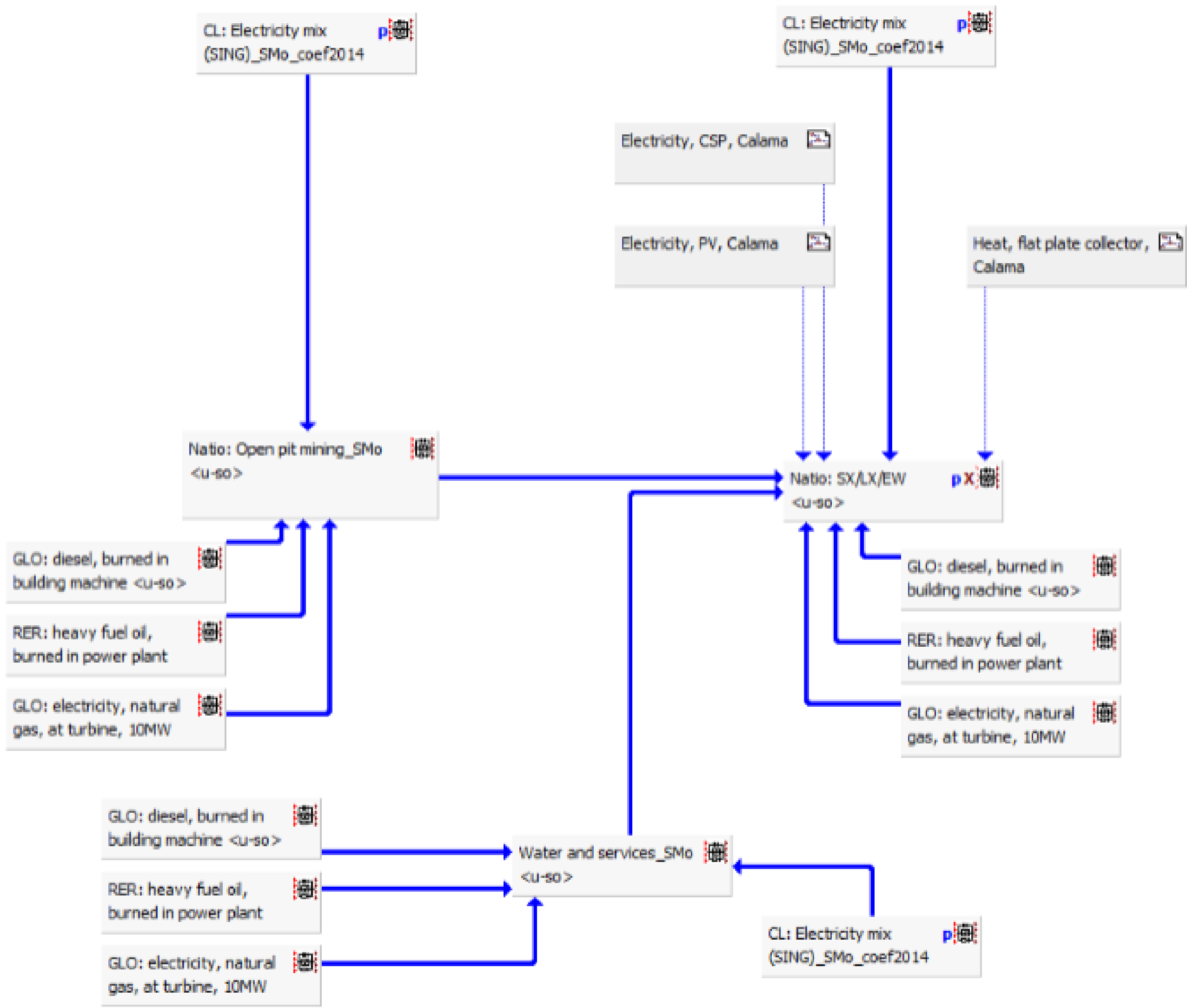
Naturally the percentage of energy supplied is the same in both cases because the estimation technique is the same and is linear.

6.4. Appendix 4: GaBi models

6.4.1. Pyrometallurgical process

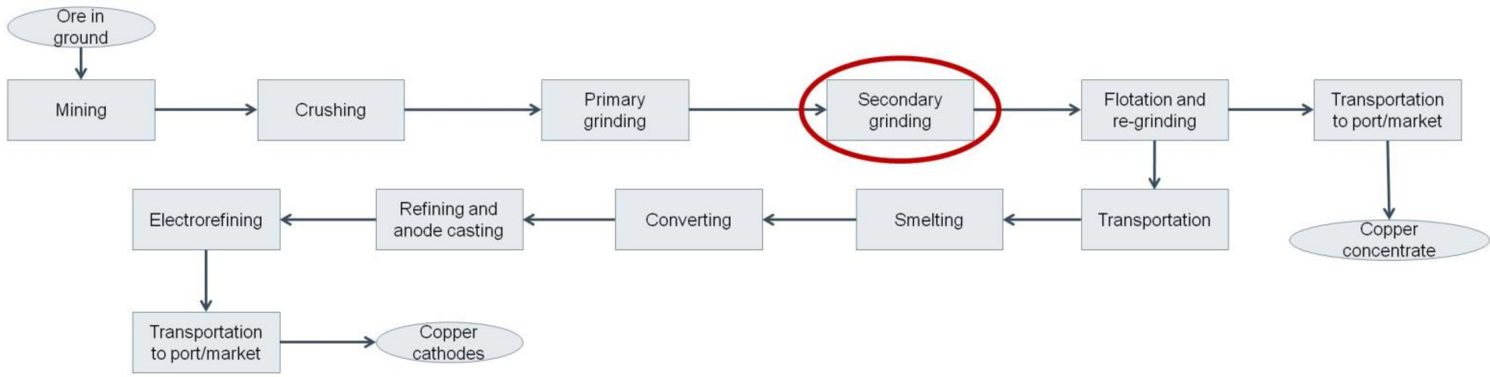


6.4.2. HYDROMETALLURGICAL PROCESS



6.5. Appendix 5: Data collection survey

This image shows one of slides which compose the survey. For every process's step data is required (secondary grinding is shown here as an example). Some specific information is required in certain steps. The survey was designed for both pyro- and hydrometallurgical processes.



General information				Process' specific information	
Operation's name	Location	Main Input origin(s)*	Main Output destination(s)*	Grinding technology	Average mineral hardness

Process' characterization													
Process	Total amount of energy consumed [kJ/kgCu]	Electricity consumed [kJ/kgCu]	Electricity usage/type of application	Fossil fuels [kJ/kgCu] or [kg/kgCu]			Fossil fuels usage			Heat demand [kJ/kgCu]	Main output (mineral) mass flow [ton/year]*	Main inputs' name and mass flows [kg/kgCu]*	Water demand [kg/kgCu]
				Diesel	Kerosene	Other	Diesel	Kerosene	Other				
Secondary grinding													

More process' relevant information according to company's experts opinion

*If there more than one origin/destination please indicate mass flows for each origin/destination in „process characteriyation table"