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Towards solar power supply for copper production in Chile: Assessment of global warming potential using a life-cycle approach

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A B S T R A C T

Solar energy technologies are a promising option to lower the greenhouse gas emissions of energy generation. Using solar technologies in energy-intensive industries located in arid climate zones is an attractive alternative for that purpose. In this work, the environmental benefit of integrating solar energy in the Chilean copper industry is explored in respect of global warming potential (GWP).

A new life cycle assessment model for copper cathodes production in Chile and the integration of three solar technologies was developed. The GWP of the production of copper cathodes was calculated considering local representative conditions for climate, energy mix, and energy demand of the industry. It was computed at 6.0 tCO_{2eq}/t Cu[2] for a pyrometallurgical process (P-Cu) and 4.9 tCO_{2eq}/t Cu for a hydrometallurgical process (H-Cu). Further contributions of this paper are the consideration of the decline in ore grade (i.e. copper content in the mineral) and the interconnection of Chile's two main power grids as sensitivities to the baseline. The interconnection of the power grids causes a GWP-reduction of 22% for P-Cu and 37% for H-Cu. In parallel, the expected lower ore grade by 2020 would increase the GWP of copper production by 10% for P-Cu and 4% for H-Cu.

If the electricity that is currently taken from the grid is exclusively fed by solar technologies, the reduction on the GWP of copper production would be up to 63% and 76% for P-Cu and H-Cu processes. These numbers do not represent the upper bound for the reduction on the GWP of copper production that can be achieved with solar technologies because the substitution of on-site fossil fuel combustion with solar energy is another interesting mitigation option, which was not considered in this study. In order to achieve even less carbon-intensive production processes, an improved understanding of the copper's industry energy flows and profiles is needed. This would allow to assess the integration of further solar energy technologies and conceive the future of *solar copper mining*.

1. Introduction

In Chile in 2014, the copper industry was responsible for 50% of the country's income from exports and 10% of its gross domestic product (National service of mining and geology, 2015). Given the relevance of this industry in the country, and as an input for many technologies worldwide, Chile will probably keep mining as relevant industry for many years. But the production of this metal is

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[2] Metric tons of carbon dioxide equivalent per metric ton of copper cathodes.

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energy-intensive, the demand accounts for 10% of the national energy demand in Chile[3] (Ministry of Energy of Chile, 2015a). It also produces major environmental impacts and particularly high greenhouse gas (GHG) emissions (Alvarado et al., 1999). The global warming challenge and the worldwide demand for low-carbon-products challenges the industry to evolve towards more sustainable practices.

Noteworthy is that around 80% of the energy demanded by the mining sector is consumed in the Atacama Desert (based on data from (Ministry of Energy of Chile, 2015a) and (National service of mining and geology, 2015)), which exhibits one of the highest solar irradiance levels on earth (Fuentealba et al., 2015). Although some solar plants have already been deployed to supply mining operations (e.g. the photovoltaic (PV) plant Calama 3 for the mine Chuquicamata or the solar thermal plant Pampa Elvira for the mine Gabriela Mistral) the total share of solar energy in the copper production process remains low. Concurrently, the country aims to diversify its economy and improve the competitiveness of the industry (Chilean Economic Development Agency, 2015). An interesting option to address both challenges simultaneously is the integration of solar and mining industries in Chile. This integration can help to improve the competitiveness and sustainability of mining operations with the use of solar energy, along with fostering the local solar industry by using products and by-products of the mining industry in local solar energy developments, adding further value to the Chilean energy sector. This paper focuses on the first: the use of solar energy technologies in mining.

The mining industry has shown to respond to many factors, such as a decline in ore grades and significant rises in energy prices, by improving processes and creating new technologies and thus expanding production capacities. From World War II to the late 1970s, the USA showed that the nonferrous metal industry was able to evolve by taking large steps in improving and increasing the capacity of the processes (e.g. by enhancing the design or by novel chemistry). Some of the principal changes involve the addition of oxygen injected through burners, tuyeres or lances into the smelting process, heap leaching/solvent extraction, the expansion of permanent cathode technology to 10–14 day plating cycles, and the application of reagent control. These improvements allowed the refineries to increase five times its production capacities, remaining nowadays as the most used techniques throughout the world copper industry (King, 2007). Further development still can be achieved. The imminent need to respond to global warming represents an opportunity to trigger another evolutionary leap in the copper mining industry. We propose to shape it by including solar technologies as the main energy supplier for its processes.

We begin by exposing some basics of copper production and its footprint calculation. Depending on the mineralogy and the ore grade there are two main methods to extract copper from the ore: pyro- and hydrometallurgical copper production processes (P-Cu and H-Cu, respectively). P-Cu, which involves smelting, accounts for 80% of the world's primary copper production and is usually applied when processing copper iron sulphides. H-Cu, which includes leaching, accounts for the remaining portion of 20% (International Copper Study Group, 2015), and is commonly used when processing copper oxides. The global warming potential (GWP) of copper production ranges from 1 to 9, with an average of 2.6 [tCO_{2eq}/tCu][4] according to data from sustainability reports of different companies from 11 countries (Northey et al., 2013). These results vary with ore grade, fuel and electricity sources, and the reporting methods and procedures used in the reports from each company (Northey et al., 2013).

The appropriate method to calculate the environmental impact of products and processes for its whole lifetime and including pre- and post-processes of use is Life Cycle Assessment (LCA). Moreover, this method has become relevant in the characterization of the emissions of mining processes, also in Latin America (Suppen et al., 2006). This approach allows quantifying the environmental impacts of products and processes over all the stages of their life cycle. LCA has already been applied in the mining industry to assess the environmental impact of different mining processes such as iron ore mining (Ferreira and Leite, 2015) and the management of tailings from a copper-zinc mine (Reid et al., 2009), among others. Moreover, a generic LCA model for mining operations was developed by Durucan et al. (2006). LCA has also been used to analyze the energy demand and the GWP of copper concentrate production (Norgate and Haque, 2010) and fine copper production through P-Cu and H-Cu (Norgate et al., 2007). Another application of LCA to the copper industry considered the historic evolution of the GWP of copper production (Memary et al., 2012). A LCA model to analyze different environmental impacts of copper production has also been exemplified with a study case in Chile (Castro-Molinare, 2014). This last study also considered sensitivities in the electricity mix but unlike this paper, analyzes a particular operation. The present study offers country-representative results and examines the performance of three specific solar technologies under the local climate conditions.

LCA has been widely applied to evaluate solar and other renewable energy generation technologies. A study reviewed 79 LCA studies that analyzed the GHG emissions of different renewable energy technologies to generate electricity and heat, including PV and solar thermal plants (Amponsah et al., 2014). Similarly, other study reviewed more than 100 case studies of LCA applied to diverse renewable energies technologies (wind, hydro, PV, and concentrated solar power (CSP)), including several impact categories (Asdrubali et al., 2015).

A systematic analysis of the existing solar technologies for reducing the GWP of the copper mining industry has not been observed. Furthermore, the early stage of the life-cycle-understanding of the Chilean solar/copper sector contrasts with the relevance of Chile in the worldwide copper market and its immense solar potential. Aiming to fill this research gap, this study approaches the problem from a life cycle perspective so that a more holistic understanding of the assessed system can be achieved. The present paper contributes to this objective by: i) presenting an up-to-date baseline of the GWP of a nation-wide representative copper production process, ii) assessing the upper limits for the GWP savings achieved when the energy from the grid is substituted by three different solar energy technologies, and iii) evaluating future scenarios considering a projection of the change in the Chilean electricity generation mix and the ore grade decline. Consequently, this paper is useful for decision-makers who are interested in both finding means for global warming mitigation in the copper mining industry and its downstream products, and understanding the potential of specific solar energy technologies in the field.

The following section presents the methodological approach and describes the assessed systems. Results are shown and discussed in Section 3.

2. Methodology

First, a Chilean industry-representative baseline for the GWP of copper cathodes production is calculated. The features of the baseline are described in Section 2.1. Then, the impact of the

[3] This includes thermal energy and electricity but not chemical energy, e.g. chemical energy used for blasting.

[4] Metric tons of carbon dioxide equivalent per metric ton of copper cathodes produced.

integration of three solar technologies on this process is explored and analyzed. The configurations of these technologies are described in Section 2.2. At last, the impact of the decline of the ore grade and the interconnection of Chile's two main power grids (Central Interconnected System, SIC, and Northern Interconnected System, SING) on the GWP of the copper production processes is assessed as described in Section 2.3.

The selected method to perform the analysis is LCA. It includes four main phases: 1) goal and scope definition, 2) life cycle inventory analysis, 3) life cycle impact assessment, and 4) interpretation of the results. The goal and scope of this work are to quantify the GWP of copper production (for its two production lines) and its sensitivity to future scenarios and the integration of specific solar technologies. The functional unit is set as a metric ton of fine copper (t Cu) in the form of copper cathodes. These models were developed in accordance with international standards (Deutsches Institute für Normung, 2006a; Deutsches Institute für Normung, 2006b).

The LCA and emissions inventories are processed with the LCA software “GaBi” (Thinkstep, 2016). The selected impact assessment method to calculate the global warming potential indicator is CML2001 GWP with 100 years scope in its updated version of April 2015 (Centre of Environmental Science (CML) Leiden University, 2015). This method assigns a characterization factor to each compound which is emitted from the assessed system. Characterization factors allow representing the emissions of the different compounds as an equivalent emission of carbon dioxide, considering both their global warming effect and the residence time that they have in the atmosphere.

2.1. Baseline assessment

As a baseline, the two regular copper production processes are assessed and evaluated. The copper production processes of the two metallurgic lines are represented in Fig. 1. The energy demand of every unit operation required for copper production is considered in the model and some operations are aggregated in stages of the process (e.g. comminution and flotation processes are considered in the concentration stage). Both P-Cu and H-Cu processes start with the mining stage, where the mineral is extracted from the ground, crushed and transported.

In the P-Cu process, the mineral is then milled and concentrated by flotation. Afterward, the copper concentrate enters a series of reactors operating at high temperature where it undergoes smelting, converting and refining, obtaining a 99.5% pure copper. The three consecutive operations are referred to as smelting. Finally, in the electro-refining, the copper anodes are dissolved, and the copper is deposited through an electrochemical reaction to produce cathodes of 99.99% purity.

In the H-Cu process, the copper is extracted from the crushed mineral by applying an acid solution (leaching, LX). This solution is then concentrated through consecutive mass transfer operations in a solvent extraction (SX) process, where copper is transferred to an organic compound and then transferred back to an acid solution with higher copper content. At last, the metal is recovered in the electrowinning (EW) operation, where copper cathodes are obtained, also at 99.99% purity (Schlesinger et al., 2011).

In the baseline the operations involved in the production of copper cathodes are grouped as follows: concentration, smelting, and electro-refining for P-Cu; and mining and LX/SX/EW for H-Cu. LX/SX/EW groups leaching, solvent extraction and electro-winning. This coarse aggregation is based on data availability and the aim of preserving the homogeneity of the data sources.

The baseline, which represents the current status of the copper production processes, was developed with an inventory of electric

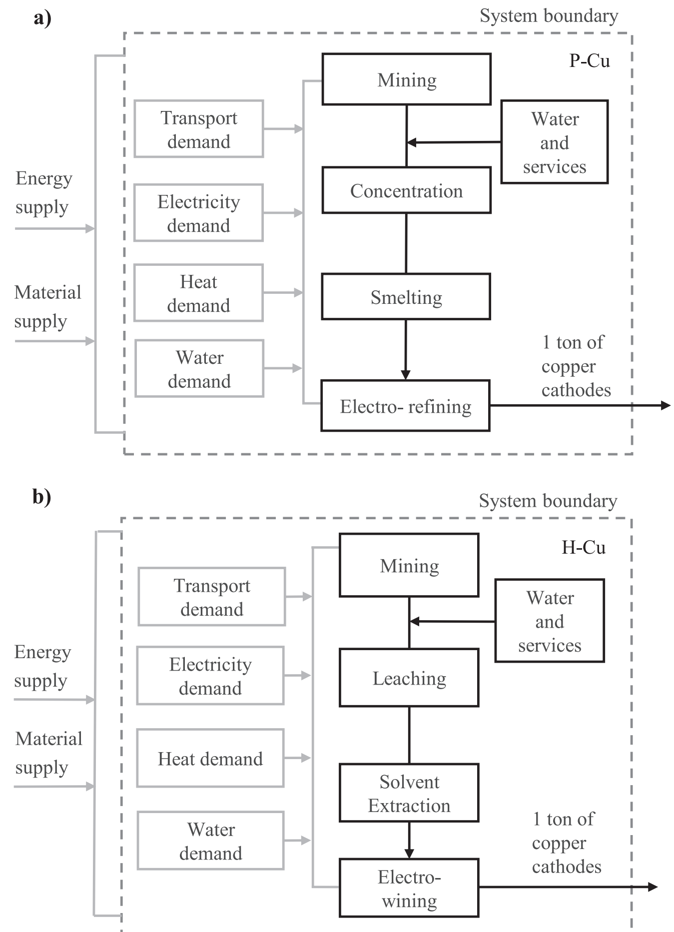

Fig. 1. Mineral processing and extractive metallurgy processes of a) H-Cu and b) P-Cu. The dotted lines show the boundaries of the system, the gray blocks, the considered energy demands, and the black blocks, the steps of the processes.

energy and fossil fuels consumption for 2014 (Chilean Copper Commission, 2015) (see Table 1). These data are directly obtained through surveys from mining companies that account for 97.6% of the Country's copper production, which is considered to be representative of the current technological status and operative practices of the Chilean industry. The diesel demand of each stage of the processes is specifically reported (Chilean Copper Commission, 2015), while the rest of the fossil fuels demand is assumed to be a ratio of natural gas and heavy fuel oil of 3:4 (following the approximate proportion in which fossil fuels are consumed in the overall industry (Verdugo et al., 2015)). These data correspond to yearly averages for the Chilean copper industry. The Chilean copper commission (2015) also reports the energy consumption due to activities not involved in the main value chain of copper, such as water impulsion and energy consumption at camps (“water and services”). With this information, the energy requirements due to transport, electricity, heat, and water demand are considered in the study.

Data from the two independent system operators (Central Chile's Independent System Operator, 2015) (Northern Chile's Independent System Operator, 2015), were used to model the electricity generation mix of 2014 for the SIC and the SING. These mixes are presented in Table 2. Copper production operations in Chile take the electricity from different power systems, depending on their location. Then, the share of energy that each system (SIC and SING) supplies to P-Cu and H-Cu processes (Verdugo et al.,

Table 1
Inventory of average specific energy demand in the Chilean copper industry as reported in (COCHILCO (Chilean Copper Commission), 2015). These values are obtained through surveys that are directly filled by the mining companies and represents 98% of the fine copper production in Chile (Verdugo et al., 2015).

Process	Electricity demand [MJ/t Cu]	Fossil fuels demand [MJ/t Cu]
Mining	817.8	7249.5
Concentration	10,810.4	208.1
Smelting	4224.8	4784.3
Electro-refining	1278.1	1300.8
LX/SX/EW	12,085.8	2865.7
Water and services	900.5	915.9

Table 2
Power grid mix for the baseline of copper production in Chile 2014

Generation technology	Share in SIC model	Share in SING model
Biomass	6%	0%
PV	1%	1%
Wind	2%	1%
Run-of-the-river hydro	20%	0%
Natural gas	15%	12%
Hydro-power	25%	0%
Oil	3%	6%
Coal	28%	80%

2015) was considered in the baseline. The models of the direct combustion of fossil fuels in the mining operations sites and the models of the on-grid electricity generation processes are based on Ecoinvent v3.1 database (Wernet et al., 2016).

All the process steps from the extraction of copper mineral until the production of copper cathodes are considered in the developed model, but the use and disposal phase of the produced copper are not. For both the H-Cu- and the P-Cu-process, GHG emissions related to energy supply are taken into account, while emissions associated with the construction of mineral processing plants are not, following the common practice in the field (Norgate, 2001). Moreover, the model developed for this study considers the GHG emissions that arise during the entire life cycle of each of the technologies used to supply energy to the process. Therefore, not only emissions arising from fossil fuel combustion during the operation of the energy plants are considered, but also the emissions related to infrastructure.

2.2. Solar technologies assessment

In this chapter, the procedures to assess the impact on the GWP of copper production when using three different solar technologies for electricity supply are described. These technologies were considered to substitute the electric power from the grid. The assessed solar technologies were: PV, concentrated solar power with parabolic through technology (CSP-PT), and concentrated solar power with tower technology (CSP-T). The use of each solar technology was assessed independently (i.e. integrating each one at a time).

2.2.1. Technical considerations

The performance of the solar plants was evaluated with 2011 weather data, with 10 min time resolution, from a meteorological station in Calama (Ministry of Energy of Chile, 2015b). This year was selected because it was the only one with full-year data availability. Based on these data, the annual direct normal irradiation is calculated at 3280 [kWh/(m^2 a)], while the global irradiation at 3614 [kWh/(m^{2}a)].

To assess the performance of the solar plants, a series of assumptions were made for each technology. For PV, the calculations were based on a single axis (polar) tracking plant with a peak capacity of 1.1 MW$_p$, composed of 4080 multi-crystalline silicon modules and two 500 kVA inverter stations. The configuration of the plant was based on Calama Solar 3 photovoltaic plant, which is currently operating in the Atacama Desert. The energy yield calculation was performed in accordance with a previously reported methodology (Duffie and Beckman, 2003). For CSP-PT a plant with a rated capacity of 50 MW and with a thermal storage capacity of 1640 MWh along with a diesel-fueled co-firing system (which represents a share of only 2% of the energy production) was used as a reference. For CSP-T the assessment was based on a 20 MW plant with a thermal storage capacity of 500 MWh with a diesel-fueled co-firing system limited to a 2% of the electricity production. A method to define the optimal positioning of the heliostats was applied (Stine and Geyer, 2001) (Lipps and Vant-Hull, 1978). The yield of both CSP technologies was calculated with a model which simulates the system performance based on an hourly control logic (Telsnig, 2015).

2.2.2. Environmental impact assessment

An LCA of each solar technology was performed to characterize its GWP impact. The emissions arising from every stage of the life cycle of the solar plants is considered. The effect of the installation of the different solar energy technologies on the GWP of P-Cu and H-Cu processes was assessed by integrating the LCA models for the solar energy technologies in the developed LCA models for copper production. In the integrated model the emissions of the solar technologies are distributed along the stages of the copper processes proportionally to its energy demand.

The functional unit in the LCA models of each solar energy technology was one electric kilowatt-hour (1 kWh$_{el}$). Each analysis considered from the extraction of the raw materials required to manufacture the components of the plants until its dismantling, as represented in Fig. 2. For the three assessed technologies, the geographic reference was Calama in the Antofagasta region, Chile. The following lifespans were considered for each technology: 25 years for PV, 30 years for CSP-PT, and 30 years for CSP-T. The emissions were allocated according to the lifespan and the energy yield of each technology.

The life cycle inventory of the solar energy technologies was deployed by adjusting data from Ecoinvent databases (Wernet et al., 2016) (Frischknecht et al., 2005) to the Chilean conditions, considering the changes in the sizing of the components of the plants. For CSP technologies, a previously reported parametrized LCA model (Telsnig, 2015) was implemented for the Chilean conditions.

2.3. Parameter variations - ore grade decline and power grid interconnection

The impacts of the copper production processes are strongly conditioned by the copper content of the ore (ore grade) (Northey et al., 2014). Therefore, it is relevant to consider the reduction in the

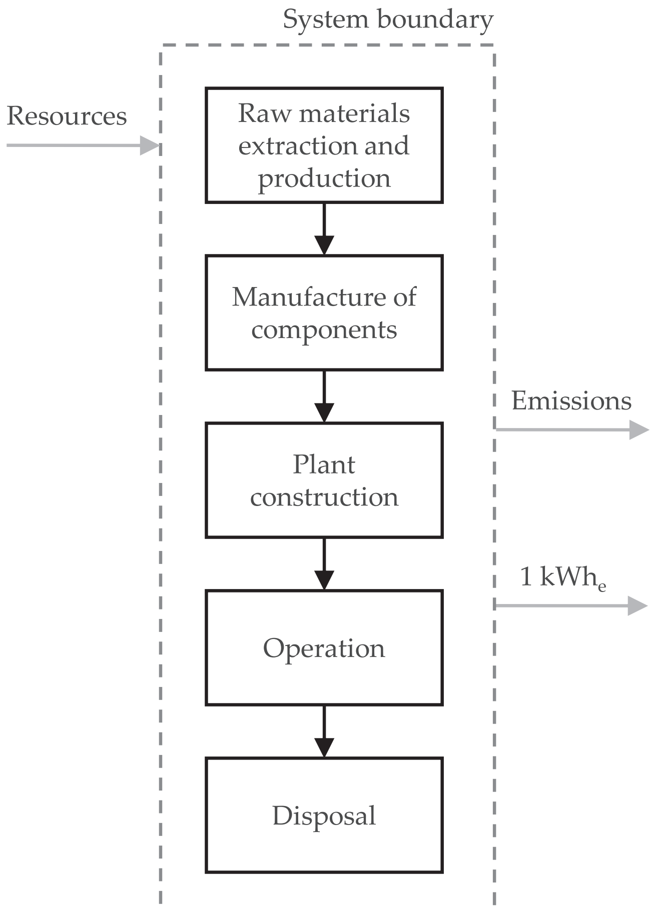

Fig. 2. Life cycle stages considered in the analysis of the solar energy technologies.

average copper ore grade in Chile when assessing the GWP and assessing future mining operations. The country's average ore grade has already declined from 1.00% in 2004 to 0.71% in 2014, which is a 30% reduction in only ten years (Consejo Minero (Mining Council of Chile), 2016). The trend is assumed to persist, reaching a grade of 0.55% in 2020. The effect that this reduction will have on the GWP of copper production was quantified by analyzing the changes in the energy requirements of the processes, based on a previously reported correlation between ore grade and energy consumption (Harmsen et al., 2013). Then, these changes were implemented on the LCA models for P-Cu and H-Cu.

Another decisive factor for the GHG emissions of copper production is the power mix taken for the production processes. By the year 2020 both main electricity grids in Chile, the SIC, and the SING grid will merge and be interconnected (Ministry of Energy of Chile, 2014). This will have an impact on the overall GHG emissions arising from the use of electricity from the grid. The effect of this phenomena on the GWP of copper production in Chile is also assessed in this study by introducing variations in the parameters of the model developed for the on-grid electricity generation.

Finally, we assessed the combined effect of the ore grade decline and the interconnection of the grids (and the consequent change in the electricity generation mix) on the GWP of a copper production process that is representative of the Chilean industry.

3. Results and discussion

This section is structured in direct response to the previous chapter. Hence, it describes the results, starting with the developed baseline, followed by the effects of the integration of the solar technologies (PV, CSP-PT, CSP-T) and finalizing with the parameter variation on ore grade and grid interconnections.

Fig. 3 summarizes the results on the GWP for copper production for both types of production processes (P-Cu and H-Cu) for the baseline in 2014 and for each configuration described in Section 2.

3.1. Baseline

The GWP of the copper production process was computed at 6.0 tCO_{2eq}/tCu for P-Cu and 4.9 tCO_{2eq}/tCu for H-Cu. The emissions can stem from local sources, e.g. from fossil fuel combustion in the mining process or from remote sources such as the electricity production mix of the power grid. The exact figures and disaggregation for the different process stages are shown in Table 3.

With these results, a representative baseline of the GWP for the Chilean copper industry was established. The results are within the range reported in previous studies (see Table 4). The differences in the GWP of copper production observed between this study and the previous ones can be explained by the use of different technologies in the processes, geographic conditions (e.g. need to pump and/or desalinate water), the ore grade, and the generation mix of the respective electrical grids. This study, in contrast to the previously reported Chilean case study (Castro-Molinare, 2014) is based on country-representative data, not on a specific operation since the processes were represented using national averages for the energy consumption of each stage of the processes.

The results also show that GHG emissions from the on-grid electricity generation represent a larger share than those from direct fossil fuels combustion at the mining operations, for both P-Cu and H-Cu, representing a 63% and 76% of the respective GWP. This is consistent with the fact that in both copper processes most of the energy is taken from the power grid. The main reasons are the concentration and the LX/SX/EW process stage. Another main driver of the GWP of the processes is the share of electricity they take from each interconnected system (SIC/SING). Particularly, H-Cu processes feed mostly from SING, which is carbon-intensive. In spite of this, the GWP per metric ton of copper produced with the P-Cu process is greater than that of the H-Cu process, due to the higher specific energy demand of the P-Cu process.

As what refers to the emissions of on-site combustion of fossil fuels, mining and smelting are process-stages with the higher contributions. To substitute these resources with solar technologies is more challenging, in contrast to solar electricity alternatives that have a proven economic competitiveness.

A limitation of the baseline is the high aggregation of operations in the process stages of the model for the H-Cu process. In the same line, more details about how the energy demand is distributed in time and about the final use of the energy resources would allow identifying further opportunities for the integration of solar energy technologies in copper production processes, beyond the alternatives assessed in this study.

3.2. Effect of integrating solar energy technologies into the Cu production processes

The resulting GWP of copper production when substituting the energy from the grid with the assessed solar energy technologies is presented in Table 5. Results show that the GHG emissions related to solar technologies (i.e. arising from construction phase) are relatively small when compared to conventional resources. Thus, the overall GWP of copper production when integrating the solar technologies depends more significantly on the resources that are being substituted, than on the selected solar technology.

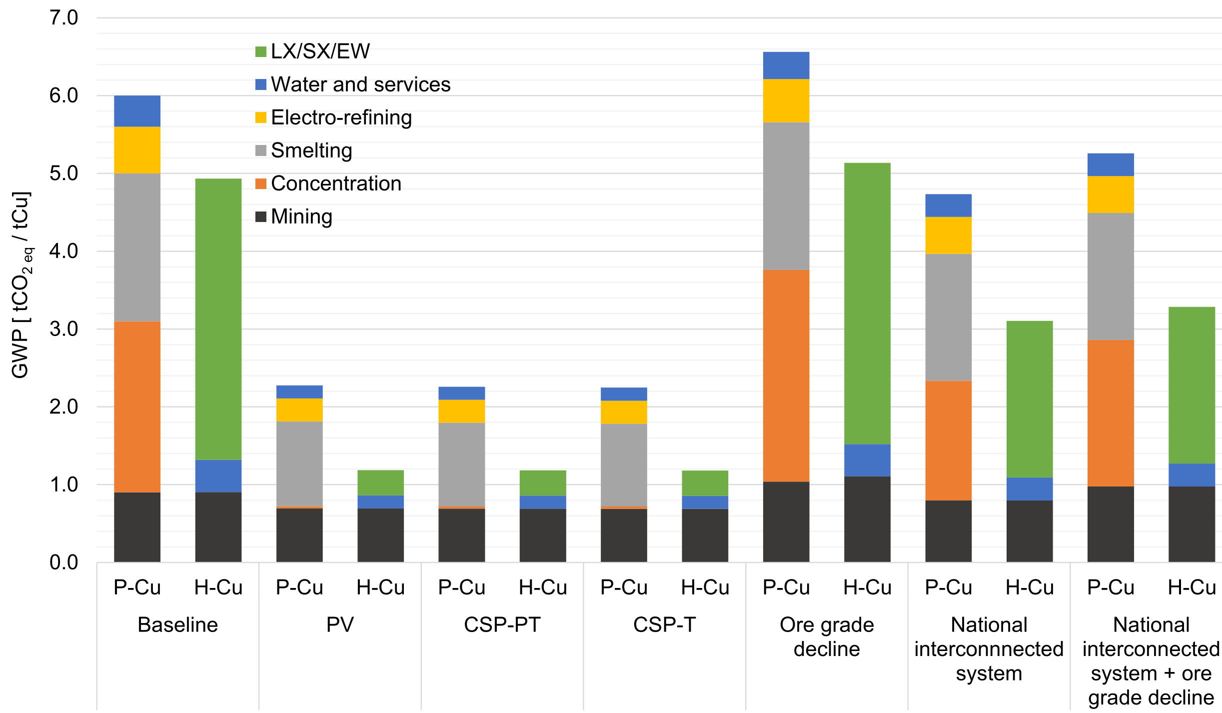

Fig. 3. GWP of the 2014 Chilean P-Cu and H-Cu copper production processes (baseline) and the effects of integrating solar technologies, of the decline in ore grade, and of the interconnection of the SING and SIC power grid. The GWP is differentiated according to the stages of the process.

Table 3
GWP of the 2014 Chilean P-Cu and H-Cu copper production processes disaggregated by process stages and emission source. *Water and services.

Source	P-Cu tCO_2eq/t Cu						H-Cu tCO_2eq/t Cu			
	Mining	W&S*	Concentration	Smelting	Electro-refining	Total	Mining	W&S*	LX/SX/EW	Total
Power grid	0.2 (22%)	0.2 (50%)	2.2 (100%)	0.9 (47%)	0.3 (50%)	3.8 (63%)	0.2 (22%)	0.2 (50%)	3.3 (92%)	3.7 (76%)
Fossil fuels	0.7 (78%)	0.2 (50%)	0.0 (0%)	1.0 (53%)	0.3 (50%)	2.2 (37%)	0.7 (78%)	0.2 (50%)	0.3 (8%)	1.2 (24%)

Table 4
Data on the GWP of copper production in comparison of different literature. Some units have been transformed from kg to metric tons for easier comparison.

Author and year	Type of process/product	GWP
Norgate et al., 2007	P-Cu	3.3 tCO_{2eq}/t Cu
	H-Cu	6.2 tCO_{2eq}/t Cu
Norgate and Haque, 2010	Copper concentrate	0.6 tCO_{2eq}/tConcentrate
Northey et al., 2013	Copper	2.6 tCO_{2eq}/tCu (average)
Castro-Molinare, 2014	Copper	4.1 tCO_{2eq}/t Cu
This study	P-Cu	6.0 tCO_{2eq}/t Cu
	H-Cu	4.9 tCO_{2eq}/t Cu

Table 5
GWP of Chilean P-Cu and H-Cu copper production processes when substituting all the current electricity mix (2014) by different solar technologies, measured in tCO_{2eq}/t Cu. The GWP savings compared to the baseline are shown in parenthesis in %.

Process chain	PV	CSP-PT	CSP-T
P-Cu	2.3 (62%)	2.3 (62%)	2.2 (63%)
H-Cu	1.2 (76%)	1.2 (76%)	1.2 (76%)

Although further detail in the representation of the operations of the processes would be valuable (especially in H-Cu), it can already be concluded, that the potential for GWP reduction is higher in the energy-intensive operations (concentration in P-Cu and LX/SX/EW in H-Cu) as compared to the low energy demanding process sections. At every mine and processing plant, this potential is bounded by the economic limit for the share of energy that solar technologies can supply.

As shown in Table 5, significant savings on the GWP of P-Cu and H-Cu processes can be achieved with the integration of solar technologies. These numbers can be reached, if the mining operations decided to acquire all the electricity needs they currently take from the power grids, from solar plants. In practice, economic factors (still) impede achieving solar penetrations close to a 100%, which is why these numbers are more frequently an upper bound for the savings that can be reached by substituting the electricity from the grid. Alternatively, these numbers can be interpreted as the marginal GHP savings (as when substituting the electricity needs of one metric ton of fine copper with solar electricity). Further, there are technical constraints of such large solar shares (e.g. need for batteries in PV) that have repercussions on the LCA model. This is active research (for a comprehensive review on the modeling challenges of expansion planning of energy storage systems consult Haas et al. (2017)) and is beyond the scope of the present work.

The GWP savings per installed capacity were also calculated for each of the different types of solar plants (considering that they are included independently) (see Table 6). This is a useful indicator to

Table 6
The GWP savings of the Chilean P-Cu and H-Cu copper production processes per MW of installed capacity of the proposed solar technologies in [kt CO_{2eq}/MW].[5]

Process chain	PV	CSP-PT	CSP-T
P-Cu	39	142	142
H-Cu	53	192	192

compare different technologies and to construct GWP abatement cost curves. These ratios are conditioned by the type of resources that are being replaced, the capacity factor, and the lifespan of the plants. CSP-PT and CSP-T show the same ratios since they replace the same technologies and have similar lifetime and capacity factors. The higher capacity factor of the CSP (given by their energy storage) allows them a larger ratio than PV.

This exercise is a first step to assess the potential of solar technologies to mitigate GHG emissions in the copper industry. Further analyses are required to understand the potential of a copper production process with an exclusively solar energy supply. For example, solar thermal applications to substitute fossil fuels could allow larger savings on the GWP of the copper production processes.

Also, more solar alternatives to be used in copper processes need to be identified. E.g. solar furnaces, which can reach the temperature required at the smelting stage of the copper production processes (Schlesinger et al., 2011; Glaser, 1958; PROMES, 2017). This technology can mature and allow to substitute the fossil fuels currently utilized in the smelting operation to reach the temperature at which the desired chemical reactions take place. Utilizing a mix of solar technologies to increase the share of energy that solar technologies supply, would also increase the GWP reduction potential of the copper industry. Therefore, innovations in copper processes and solar energy applications that allow increasing this share, and even to conceive a 100% solar copper mining operation, need to be identified and assessed.

3.3. Effects of the decline in ore grade and the interconnection of the SING and SIC power grids

A lower ore grade makes the processes more energy demanding. This results in a larger GWP (Harmsen et al., 2013) as compared to the processes currently in place. For the projected decrease in the ore grade (from 0.71% in 2014 to 0.55% in 2020 if the trend reported for the period from 2004 to 2014 (Consejo Minero (Mining Council of Chile), 2016) is assumed to persist), the GWP of copper production is calculated at 6.6 [t CO_{2eq}/t Cu] for P-Cu and 5.1 [t CO_{2eq}/t Cu] for H-Cu. Relative to the baseline, this is an increase of 10% and 4%, respectively. The decline in the ore grade does not affect every process stage equally. The energy requirements rise only at the mining and concentration stages. Other stages where the copper concentration of the inputs is set by design are not affected by this phenomenon. This explains why the decline in the ore grade affects differently to P-Cu and H-Cu processes.

The change in the GWP of the copper production processes due to the interconnection of the power grids results in 4.7 [t CO_{2eq}/t Cu] for P-Cu and 3.1 [t CO_{2eq}/t Cu] for H-Cu. This lowers the GWP by 22% for P-Cu and 37% for H-Cu, since a lower a share of carbon intensive generation technologies is expected. This effect is more relevant in the H-Cu production process since the electricity from the grid, and specifically from the carbon-intensive SING-grid, represents a larger share of the overall energy demand of that process.

[5] 1000 metric tons of carbon dioxide equivalent per installed megawatt of a solar technology.

When considering the combined scenario (ore grade decline and connection of the grids) the ore grade decline is compensated and the resulting GWP is 5.3 [t CO_{2eq}/tCu] for P-Cu and 3.3 [tCO_{2eq}/tCu] for H-Cu. This is equivalent to a 12% and 34% decrease as compared to the baseline.

3.4. Conclusions

The paper proposes a new life cycle assessment for both, the copper cathodes production processes and the integration of solar technologies in Chile. The GWP of the 2014 Chilean copper production was determined at 6.0 [t CO_{2eq}/t Cu] for the pyrometallurgical (P-Cu) and 4.9 [t CO_{2eq}/t Cu] for the hydrometallurgical (H-Cu) process. These values are highly sensitive to the source of the grid-based electricity generation. With the interconnection between the two main Chilean power grids, SING and SIC, and the subsequent lower GHG emission level of the combined grid, they are expected to decline by 22% and 37% for P-Cu and H-Cu in 2020 as compared to the status before. The expected ore grade decline by 2020 will increase the GWP of copper production by 10% and 4% for P-Cu and H-Cu. The combined effect of the interconnection and the ore grade decline will lower the GWP by 12% for P-Cu and 33% for H-Cu. If the conventional energy is substituted by solar energy, much lower GWP levels can be reached.

When substituting 100% of the electricity from the grid by the assessed solar energy technologies, the GWP of P-Cu process is reduced by 62%–63%, while the GWP of H-Cu process declines by 76%. While these savings are an upper limit for the GWP reductions when substituting electricity from the grid, assessing further reductions that could be achieved when displacing fossil fuels (for heat and transport) is still pending.

Other environmental impacts and the economic feasibility of the proposed alternatives also need to be covered in future research, along with the identification of more opportunities to integrate solar energy in mining. At last, further development in mining processes design and solar applications must be addressed to enable a higher share of solar energy and to fully take advantage of this opportunity towards a cleaner production of copper.

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Acronyms

SING	Northern Interconnected System (Sistema Interconectado del Norte Grande)
SIC	Central Interconnected System (Sistema Interconectado Central)
COCHILCO	Chilean Copper Commission (Comisión Chilena del Cobre)
H-Cu	Hydrometallurgical copper production
P-Cu	Pyrometallurgical copper production
LX/SX/EW	Leaching, solvent extraction, and electro-wining
LCA	Life cycle assessment
GHG	Greenhouse gasses
GWP	Global warming potential
PV	Photovoltaic
CSP-PT	Concentrated solar power parabolic trough
CSP-T	Concentrated solar power tower

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