Journal of Cleaner Production 174 (2018) 389–400

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

The effect of mine aging on the evolution of environmental footprint indicators in the Chilean copper mining industry 2001–2015

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ARTICLE INFO

Article history:
Received 20 April 2017
Received in revised form
7 September 2017
Accepted 27 October 2017
Available online 27 October 2017

Keywords:
Chile copper mining
Footprint
Ore grade
Energy
Water
GHG emissions

ABSTRACT

Abundant evidence suggests that the massive global exploitation of copper mines over the last two decades led to mine aging expressed as ore grade reduction, deepening of open pits and underground operations, hardening of the rock, and increasing stripping ratios. These processes have affected the evolution and change of key environmental footprint indicators. Copper ore grade decline seems the most important of these factors and depends on variables including the rate of extraction, ore deposit geological features, introduction of new technologies, the copper price and its co-products, and the discovery and exploitation of new ore deposits. From 2001 to 2015 Chile increased its copper production by 22% and produced overall 80 million tons of copper, more than it produced in the entire 20th century. This paper explores the effects of mine aging on three key environmental footprint indicators: energy and water consumption, and greenhouse gas emissions. Electric energy consumption per ton of copper should grow in the coming decade at a significantly slower rate than in the last fifteen years because of the slowdown of the ore grade decline in mill concentrators. Additionally, a steeper decrease is expected for the emission of greenhouse gases per ton of copper.

1. Introduction

Vast evidence suggests that current copper resources in the ground can meet the growing demand over the next decades. Constraints on using these resources for production may mainly result from social and environmental (Schodde, 2010; Mudd et al., 2012) concerns. Elshkaki et al. (2016) and Gordon et al. (2006) nevertheless concluded that the world would face a shortage of copper produced in mines in the future. Their approach resembles Meadows et al. (1972) adopted in the Club of Rome Report. Tilton and Lagos (2007) refuted Gordon et al. (2006), and this debate continues.

In contrast, Northey et al. (2014) developed a model to estimate “peak copper” and established such a concept in many copper producing countries, assigning diminishing production after the peak to lack of knowledge of future reserves. He then concluded that constraints for the production of this metal in mines in the future would be more likely economic and environmental issues relating to energy and water consumption, and Greenhouse Gas emissions (GHG). It should be noted that Meadows et al. (1972), Gordon et al. (2006), Northey et al. (2014) and Elshkaki et al. (2016) assumed that copper resources in the ground would remain fixed in the future, disputing the well-established historic data by USGS and by Schodde (2010) who find copper reserves and resources never ceased to increase sufficiently in the past to produce and deliver the metal to the market at competitive prices.

Individual mines undergo an aging process (Mudd et al., 2013) whose end point is their closure, which occurs when the ore grade is too low for economically viable extraction. This process can be extended to all operating mines, but not necessarily to mining countries or districts, because new deposits are being discovered, some of them with ore grades above the national and even the global average (Schodde, 2010; Mudd, 2010, Mudd et al., 2013; Northey et al., 2014). Therefore, it remains important to estimate effects of mine aging in a district or a country.

This paper extends the concept of mine aging to other variables beside ore grade decline, and includes deepening of open pits and of underground mines, more refractory ore, and increasing stripping ratios.

Knowledge has been generated regarding the consequences of mine aging on rising energy and water consumption, growing waste generation, as well as Greenhouse Gas emissions (Ayres et al.,

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https://doi.org/10.1016/j.jclepro.2017.10.290

2002; Kuckshinrichs et al., 2007; Mudd, 2009, 2010, Mudd et al., 2012, 2013; Northey, 2011, Northey et al., 2013, 2016; Norgate and Jahanshahi, 2007; Gordon et al., 2006; Elshkaki et al., 2016; Spuerk et al., 2016; Ali et al., 2017). Ore grade decline also has a detrimental effect on the economics of the business because mine and plant capacity must periodically expand to maintain the level of production (Crowson, 2012; Calvo et al., 2016).

In the half century before 2005 the rates of ore and rock extraction were small in comparison with present ones and the discovery of new deposits was relatively common (Schodde, 2010). As a result, copper ore grades remained almost constant (West, 2011), which may have been due to a combination of declining ore grades in existing mines and high grades in new operations (Crowson, 2012). However, from 2005 on ore grades decreased by 25% (Calvo et al., 2016). Such a severe decline of the average ore grade is possibly related to innovations and better copper price perspectives that allowed the economical exploitation of lower grade deposits (West, 2011).

Chile's copper mines were massively exploited from 2001 to 2015 and suffered notably from the aforementioned aging processes. The country produced 80 million tons of copper in cathodes and contained in concentrates, which represented 33% of the metal produced in mines globally, and 16% more than Chile produced in the 20th century. The overall ore grade decline, including the two main processing methods, was 51% during the period. Furthermore, the country was able to increase its copper production only 7% from 2004 on (5.4 million tons of copper), even though it put into operation six new mines including Spence in 2007, Gabriela Mistral in 2008, Esperanza in 2011, Caserones, Ministro Hales and Sierra Gorda in 2014, and also expanded the production capacity of existing ones (Cochilco, 2016a).

This paper has the purpose of analyzing the trends generated in three key environmental footprint indicators of Chilean copper mining in the 2001–2015 period as a consequence of the mine aging processes experienced during these years. These indicators are energy and water consumptions and GHG emissions, which are critical to the production structure of copper primary products (Santero and Hendry, 2016).

These variables have been selected because robust data for copper production is provided by the Chilean Copper Commission (Cochilco), which allows not only to determine its trends, but also to identify some of the main causes for such trends, and to recognize the limitations and drawbacks of the data and analysis methods. One drawback of using the average values is that no estimates of maximum and minimum, or standard deviation is provided for each average value.

Analysis was focused on the effect of aging on electric and fuel burned energy consumption, on water consumption and on direct and indirect GHG emissions, denominated scopes 1 and 2 respectively. Direct emissions are generated by fossil fuel burning, whereas indirect emissions are generated by the production of electricity. Regarding GHG emissions, scope 1 is derived from fuel consumption data, provided by Cochilco (2014, 2016b), and indirect emissions are estimated from information by Cochilco (2016c), Schlömer et al. (2014) and Comision Nacional de Energia (CNE, 2016), the National Energy Commission. Many companies and organizations have adopted this approach (Northey et al., 2013; Matthews et al., 2008; Mudd et al., 2012). Additionally, others like Norgate's studies (Norgate and Rankin, 2000; Norgate and Jahanshahi, 2007, 2011, Norgate and Haque, 2010a) usually consider embodied energy which, additionally to scopes 1 and 2, includes the inputs and outputs required to supply the materials and equipment used in the primary copper processes (scope 3).

The subsequent section describes the methods and data sets used, the third section contains the results and discussion of trends of the studied variables, and section four concludes.

2. Methods

To obtain the main drivers of the environmental footprint indicators, the copper production processing methods were categorized into mining extraction (open pit and underground mining), mill concentrator plant (Fig. 1a), and Leach/SX/EW processes (Fig. 1b). Mill concentrator processes accounted for approximately 81% of mine copper refined globally in 2015, while Leach/SX/EW processes made up the rest (ICSG, 2016). In Chile, these values were 69% and 31%, respectively (Cochilco, 2016a). Regarding ore extraction methods, 86% of copper production originated in open pits and the rest in underground mining operations in 2015. All ores from underground mines were processed via mills. An analysis of the potential new mines and expansion of existing ones, concludes that oxide mining will decrease in relative importance in the next decade, as deposits will run out to uncover the sulfide deposits which are underneath (Cochilco, 2017). Virtually all mining production growth will be based on exploitation of primary sulfides, using the traditional process.

Open pit and underground operations include several unit processes such as drilling, blasting, loading, transport, and primary crushing. The product from mines is the ore fed to mills, also denominated concentrator plants, and to Leach/SX/EW processes. Mill concentrator plants include secondary and tertiary crushing, transport, milling, classification, flotation, solid/liquid separation, filtration and tailings transport and disposal. The products of mill plants are concentrates which must then be smelted and electrorefined to produce cathodes. Smelting and refining can be carried out anywhere in the world because concentrate transport is economically viable. Leach/SX/EW processes include secondary crushing, ore transport, leaching, solvent extraction and electrowinning. Sometimes, it includes agglomeration before leaching. Leach/SX/EW processes produce cathodes. Fig. 1b shows Run off Mine (ROM) as one of the products of mining. ROM ore is extracted directly after blasting and does usually not go through primary crushing. It is piled separately so that it can be leached, a process called ROM leaching.

This paper analyzes underground and open pit mines, concentrator plants and Leach/SX/EW plants. Smelting and refining are excluded, because in 2015 only about 26% of the concentrates were smelted in Chile and 16% of copper anodes were electro-refined in the country, respectively (Cochilco, 2016a). The rest of concentrates were exported with copper in concentrates typically referred to as copper contained, but this term can also be applied to cathodes produced by any of the two methods indicated in Fig. 1a and b.

Table 1 shows the decrease of average ore grade in Chilean mining, in mines, concentrator plants and Leach/SX/EW plants. Run off Mine (ROM) ore grades declined slightly from 0.47% to 0.36% between 2007 and 2015, the only publicly available data (Cochilco, 2016a).

Ore grade decline causes several effects. More ore has to be mined and processed to maintain the level of production. More mining means extra drilling, loading and haulage, and more processing translates into expanding concentrator plants and Leach/SX/EW installations. Additionally, lower ore grade usually signifies smaller particle mineralization, and, therefore the need to mill the ore to a finer particle size. Finally, more water is needed to maintain the level of copper produced.

With deepening pits, haulage distance increases, and usually the waste to ore ratio, known as the stripping ratio, too. Deeper underground mines also cause longer haulage distances, and require more energy for ventilation. Moreover, deep underground mines