Resources, Conservation and Recycling 83 (2014) 190–201

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining

S. Northey[a,*], S. Mohr[b], G.M. Mudd[a], Z. Weng[a], D. Giurco[b]

[a] Environmental Engineering, Department of Civil Engineering, Monash University, Clayton, VIC 3168, Australia
[b] Institute for Sustainable Futures, University of Technology, Sydney, Ultimo, NSW 2007, Australia

ARTICLE INFO

Article history:
Received 20 May 2013
Received in revised form 26 August 2013
Accepted 13 October 2013

Keywords:
Copper
Mining
Ore grade decline
Resource depletion
Scarcity
Peak minerals

ABSTRACT

The concept of "peak oil" has been explored and debated extensively within the literature. However there has been comparatively little research examining the concept of "peak minerals", particularly in-depth analyses for individual metals. This paper presents scenarios for mined copper production based upon a detailed assessment of global copper resources and historic mine production. Scenarios for production from major copper deposit types and from individual countries or regions were developed using the Geologic Resources Supply-Demand Model (GeRS-DeMo). These scenarios were extended using cumulative grade-tonnage data, derived from our resource database, to produce estimates of potential rates of copper ore grade decline.

The scenarios indicate that there are sufficient identified copper resources to grow mined copper production for at least the next twenty years. The future rate of ore grade decline may be less than has historically been the case, as mined grades are approaching the average resource grade and there is still significant copper endowment in high grade ore bodies. Despite increasing demand for copper as the developing world experiences economic growth, the economic and environmental impacts associated with increased production rates and declining ore grades (particularly those relating to energy consumption, water consumption and greenhouse gas emissions) will present barriers to the continued expansion of the industry. For these reasons peak mined copper production may well be realised during this century.

1. Introduction

Copper (Cu) continues to enjoy a strong and growing demand, due to its wide use across a variety of applications from electrical and pipeline infrastructure to electronics. Given the rapid industrialisation in China occurring in recent years, with India following a similar path and other regions expected to follow in the medium term (e.g. South America, Africa), it can reasonably be expected that demand for Cu will continue to stay strong and grow for many decades to come.

The environmental impacts of Cu mining are closely related to the grade (i.e. the copper concentration) of ore being mined (Norgate and Haque, 2010). In general, mines will target higher grade ores since these represent richer returns. Over time, mines will deplete their higher grade resources and move to lower grade ores, leading to a gradual decline in average Cu ore grades over time, as documented for Australia (Mudd, 2010), USA (Ruth, 1995) and Canada and Papua New Guinea (Mudd and Weng, 2012) or globally (Crowson, 2012). At almost all major Cu mines which are close to 100 years old (or older), such as Bingham Canyon (USA), El Teniente (Chile) or Mt Lyell (Australia), a gradual long-term decline in ore grade is clearly evident (Crowson, 2012; Mudd, 2010).

As ore grades decline, a larger amount of material has to be moved and processed to achieve the same unit of produced metal. The size of mines is also increasing as low grade Cu deposits are typically larger ore deposits and achieve increased financial benefits by operating at larger economies of scale (Mudd and Weng, 2012). The combination of increased mine size and declining ore grade results in increases in the rate of waste rock removal, tailings generation and area of local habitat disturbance. Declining ore grades also have impacts on other areas of environmental concern, such as increases in diesel and explosives consumption within the mine itself and also the water and energy consumption within ore processing facilities (Norgate and Jahanshahi, 2010).

At present, global average mined ore grades for Cu are about 0.62% Cu with annual production about 16 million tonnes of copper per year (Mt Cu/yr) (Mudd and Weng, 2012). Based on a recent global study of reported Cu mineral resources (representing

* Corresponding author. Present address: Process Science and Engineering, CSIRO, Clayton, VIC 3168, Australia. Tel.: +61 395452265.
E-mail addresses: stephen.northey@csiro.au, stephen.northey@gmail.com (S. Northey).

0921-3449/$ – see front matter. Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.resconrec.2013.10.005

1780.9 Mt Cu), average ore grades were about 0.49% Cu, suggesting that future declines in ore grades are likely to be slower than observed historically (Mudd et al., 2013).

Although there has been considerable debate and analysis of the concept of 'peak oil' (e.g., Bentley, 2002; Feng et al., 2008; Smith, 2012; Sorrell et al., 2009), there has been very little research assessing the concept of 'peak metals' and associated issues (May et al., 2011; Prior et al., 2012) – especially specific case studies of individual metals such as Cu. In simple terms, peak oil is based on the fundamental notion that resources are finite and being rapidly depleted, or alternatively production is moving from the cheap readily accessible oil to the more remote and expensive oil resources. While oil reservoirs are typically large geologic structures, metal deposits are often small features hidden in regional geological complexity. This means that it requires considerable effort and investment not only to locate a metal deposit but also to demonstrate that it will prove economically viable to mine it. To minimise exploration and development costs, it is common practice in the mining industry not to drill an orebody out entirely, but to delineate an extractable reserve using a minimal amount of drilling, with subsequent conversion of resources to mineable reserves during the lifetime of a mine. Over time, ongoing greenfield and brownfield exploration can continue to find new deposits or expand resources at operating mines, changing market conditions can make a project profitable (or otherwise), or new technology can enable previously uneconomic projects.

One key difference between Cu mining and oil is that Cu mines aim to extract a minute fraction of the ore – i.e. the copper – with the remainder being waste (or tailings). Ongoing exploration can also affect recoverable Cu resources, as new discoveries can lead to major increases (e.g. Olympic Dam in Australia, Pebble in USA or Oyu Tolgoi in Mongolia; Mudd et al., 2013) – with exploration success globally still effectively outpacing annual production (Schodde, 2010). Finally, although oil is consumed when used, most Cu remains in service and can be readily recycled (subject to economics, regulatory policies, consumer and industry behaviour, and so on).

It is the long-term trends in Cu mines over decades to centuries that are crucial to understand with respect to "peak copper mining". The two most important aspects are ore grades and remaining recoverable mineral resources, while others may include mineral processing technology, demand/supply and economics, environmental constraints (especially energy and water consumption, greenhouse gas emissions, land use, etc.), or labour.

A common approach to modelling the environmental impacts of Cu mining is through life cycle impact assessment or LCIA. There tends to be an inverse exponential relationship between ore grade and environmental impacts, such as energy, water and greenhouse gas (GHG) emissions intensity per tonne of Cu produced. An example for GHG emissions is shown in Fig. 1, with similar results being found for energy and water (Norgate and Jahanshahi, 2010).

Given the links between increased environmental impacts and ore grade declines, an improved understanding of the future prospects for Cu mining is important to drive discussion between policy makers, mining companies and the broader community. To date there has been no study that has modelled future Cu ore grades for individual countries or deposit types based on an extensive global Cu resource database. This paper provides an assessment of the possible rate and degree of Cu ore grade decline into the future. Two global Cu supply scenarios are modelled based on a comprehensive Cu resource database. The implications of these scenarios are then briefly discussed with the aim of informing further research to predict the environmental impacts of Cu mining operations.

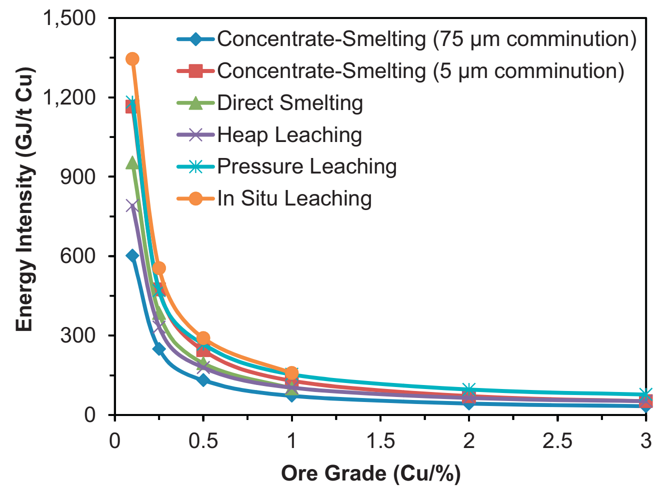

Fig. 1. Greenhouse gas emissions intensity of different processing pathways for copper mining (redrawn from Norgate and Jahanshahi, 2010).

2. Model and methods

2.1. Overview of the production and ore grade decline modelling

The historic and future production of copper has been modelled based on estimates of the Ultimate Recoverable Resource (URR) for individual countries and deposit types. The production scenarios have been modelled using the 'Geologic Resources Supply – Demand Model' (GeRS-DeMo) developed by Mohr (2010). The scenarios produced using GeRS-DeMo have been used to estimate the progression along cumulative grade-tonnage curves for each country or deposit type from 2010 onwards. This gives an estimate of the future rate of copper ore grade decline.

2.2. Defining the ultimate recoverable copper resource

The URR is an estimate of the total copper that society will recover from mineral deposits, both historically and into the future. Determining the URR for individual countries and deposit types requires estimates of the historical rates of Cu production and the remaining available Cu resources.

2.2.1. Historical copper production

The annual data for historical mined Cu production by country was sourced and cross-checked from a variety of references:

- *World Mineral Statistics Archive* of the British Geological Survey, years 1913 to 2010 (BGS, 2012);
- *International Historical Statistics series* by Mitchell (1993, 1995, 1998);
- *Minerals Yearbook* of the (former) U.S. Bureau of Mines, years 1933 to 1993 (USBoM, various);
- *Minerals Yearbook* of the U.S. Geological Survey, years 1994 to 2010 (USGS, various);
- *World Non-Ferrous Metal Production and Prices*, 1700–1976 *by* Schmitz (1979).

Using these data sources, an estimate of the cumulative mined Cu production for each country or major region until 2010 was produced (provided in the electronic supplement).

Gerst (2008) provides an annual percentage of Cu production by geological or mineralisation deposit type from 1800 to 2000. During 2010, the proportion of Cu produced from porphyry, volcanic massive sulfide (VMS), sediment-hosted and other deposit types