Science of the Total Environment 651 (2019) 1764–1775

Contents lists available at ScienceDirect

Science of the Total Environment

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

Global warming potential and total material requirement in metal production: Identification of changes in environmental impact through metal substitution

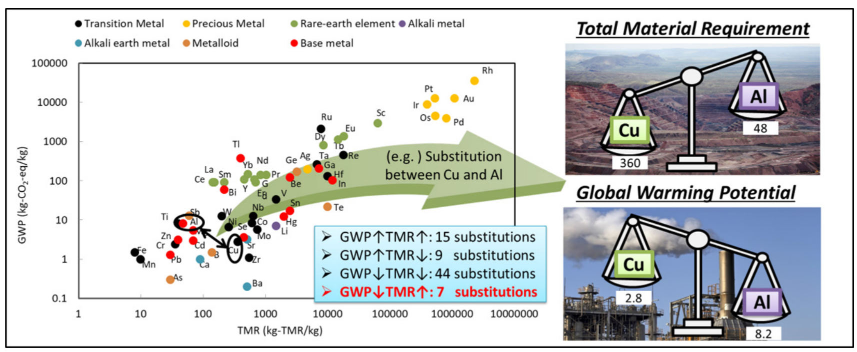
Shoki Kosai *, Eiji Yamasue

Department of Mechanical Engineering, College of Science and Engineering, Ritsumeikan University, Shiga, Japan

HIGHLIGHTS

- Interaction of environmental consequences of mining activities is identified.
- Total material requirement is employed as an environmental indicator.
- Relations between GWP and TMR for 59 metals are assessed.
- 40% of metal substitute options cause an additional environmental impact.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 August 2018
Received in revised form 6 October 2018
Accepted 7 October 2018
Available online 09 October 2018

Editor: Deyi Hou

Keywords:
Mining
Life cycle impact assessment
Metal replacement
GWP

ABSTRACT

In view of the increasing demand for metal use, it is of significant importance to evaluate the environmental impact of metal production. The global warming potential (GWP) in the process of metal production has often been focused upon as a major indicator for evaluating the burden on the environment. Moreover, the environmental impact and mineral exploitation arising from metal ore mining activities, which generate unavoidable mine wastes and have an impact on the ecological biodiversity, cannot be ignored. The major factors for determining the intensity of resource exploitation being the ore grades and strip ratio, the existing indicators for land use employed in the life cycle assessment (LCA) may not fully cover the criteria of the impact of metal mining on the environmental system. Therefore, this study employs the method of total material requirement (TMR) assessment, involving not only the direct and indirect material inputs but also the hidden flows, which are particularly associated with mine wastes. Firstly, the methodology of computing the TMR in the process of metal production is developed. Next, the relation between the GWP and TMR for 58 metals is assessed and finally, the environmental impact through metal substitutes is evaluated from the perspectives of the GWP and TMR. This analysis could identify some of the aspects overlooked in the previous environmental criteria that were concentrating on greenhouse gas emissions and global warming. The developed algorithm may be useful in identifying appropriate metal substitutes, considering the environmental impact.

1. Introduction

In the last few decades, the increase in global population, heavy industrialization in developing countries, rapid electronic innovations,

* Corresponding author.
E-mail address: kosai0203@gmail.com (S. Kosai).

https://doi.org/10.1016/j.scitotenv.2018.10.085
0048-9697/

and infrastructure transition have dramatically changed the global metal landscape (van der Voet et al., 2013). In view of the increasing demand for metal use, an evaluation of the environmental impact of metal production is of significant importance.

Life cycle (impact) assessment (LCA) is a well-developed tool for evaluating the potential environmental impact throughout the lifetime of a product (ISO, 2006). Inventory database (e.g., ecoinvent) is used to carry out LCA under the various production processes (Swiss Centre for Life-Cycle Inventories, 2007). Environmental impact of metal production has also been evaluated in the context of LCA (Kolotzek et al., 2018; Bach et al., 2016). Pizzol et al. assessed the consequences of toxicity of metals in the ecosystem by comparing various LCA techniques including Stepwise 2006, Impact 2002+, EDIP 2003, Eco-Indicator 99, CML 2001, TRACI 2, ReCiPe, and USEtox (Pizzol et al., 2011). In metal production particularly, ReCiPe endpoints (Huijbregts et al., 2017) have often been utilized to illustrate critical environmental consequences (Graedel et al., 2012; Nassar et al., 2012; Nassar et al., 2015a; Graedel and Nuss, 2014; Harper et al., 2015).

Among the various types of environmental impacts, global warming issues have specifically focused on the processes from ore mining and concentration through smelting to metal refinery. Nuss and Eckelman evaluated the global warming potential (GWP) of 63 metals including the minor metals (Nuss and Eckelman, 2014). The carbon dioxide emissions and energy input throughout the process of metal production (United States Department of Energy, 2010; Morley and Eartherley, 2008) have been used as major indicators in evaluating the environmental impact, particularly associated with global warming. Various researchers expend time and effort on developing the energy and CO_2 inventory data of metal processing (e.g., rare earths (Sprecher et al., 2014; Koltun and Tharumarajah, 2014)).

Notwithstanding the use of GWP as a well-known indicator of environmental impact (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010; European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2012), the effects of metal ore mining activities cannot be ignored (Kosai et al., 2018). All mining activities change the landscape of the earth and global mining activities move over 57 billion tons of land every year (Douglas and Lawson, 2000). As the process of extraction primarily consumes the stock of natural capital, mining activities, directly and indirectly, have multiple impacts on the environmental systems (Franks et al., 2010).

The environmental impact arising from mining activities is largely the result of generation of mine waste (Bridge, 2004; Prior et al., 2012; Mudd, 2007) and changes in the land structure (Schmidt and Ostfeld, 2001; Patz et al., 2004). It has been stressed that mine waste, like physical and chemical pollution, presents a great risk to human health and the natural environment (Bridge, 2004). Physical pollution is caused by the release of suspended particulates, such as dust into the air, water or onto the land, and has been a major concern with regard to mining activities throughout the ages (Ripley et al., 1996). Chemical pollution is basically caused by the ingress of reagents, used in processing raw material, into the environment or by the natural occurrence of chemical reactions of targeted raw materials (Mudd, 2007). As the characteristics of mine waste are largely unknown, the successful rehabilitation of mining sites is of paramount importance to avoid harmful reactions in the bio-ecosystem (Prior et al., 2012; Sánchez, 1998; Jenkins and Yakovlova, 2006). Historically, <1% of global land surface being utilized for mining activities, the environmental impact was dismissed and considered inconsequential from the geographical perspective (Hodges, 1995; Marsh, 1995). The introduction of an ecological perspective has led to a reassessment of the significance of these impacts (Pascal et al., 2008; Murguía et al., 2016). Both mine waste and land change intervene in ecological systems, resulting in environmental and ecosystem damage, such as forest fragmentation, pathogen introduction, and mitigation of biodiversity (Bridge, 2004; Sandifer et al., 2015).

Besides these, the various inputs including water and energy required in the mining process must be taken into account. In particular, the relation between energy utilization and mining activities was highlighted in the context of global warming issues (Bridge, 2004; Mudd, 2007). The higher the energy input required, the more vulnerable is the process to energy-related issues, specifically to greenhouse gas emissions (Mudd, 2010a).

Considering the significance of the relation between environmental burden and mining activities, focus on GWP alone may lead to a short-sighted analysis of the environmental impact of metal production. The following comparison between copper and aluminum is an apt example: Aluminum is obtained by the electric refining of bauxite at a high temperature with a significant input of energy, whereas the process of reducing copper oxide to obtain copper does not require such a large amount of energy. Therefore, the GWP of aluminum is greater than that of copper (Nuss and Eckelman, 2014). On the other hand, the intensity of mineral exploitation for copper mining would be greater than that for aluminum as the ore grades of copper and aluminum are 0.5–1% and 10–15%, respectively (JOGMEC, 2014). The importance of ore grade for determining the intensity of mining activity is presented in detail in Section 2. Hence, a comparative analysis of the indicators for evaluating the environmental risk in metal production is of paramount importance.

Further, the comparative analysis between GWP and TMR would assist in identifying the potential to increase or decrease the environmental impact through metal substitution. Various uncertainties in metal price, processing cost, geopolitical stability and metal depletion have raised the security of continuous metal supply to an alarming extent. Critical metal strategies have been proposed in the national resource policy narratives in the US (United States Department of Energy, 2010), EU (European Commission, 2010) and Japan (Nakamura and Sato, 2011). In order to address these critical metal issues, metal substitutes are recommended, in addition to the reduction of metal utilization, reuse and recovery of metals used in products (Graedel et al., 2015a). Many researchers have put in huge efforts in identifying alternative materials to be substituted for the original critical metals (Graedel et al., 2015b). It is of interest to evaluate the change in environmental impact due to the use of metal substitutes.

Therefore, the objectives of this paper are to propose an indicator related to the intensity of mineral exploitation for evaluating the environmental impact arising from mining activities, to conduct a comparative analysis with the global warming issues, and to identify the potential to increase/decrease the environmental impact through metal substitutes.

The paper is structured as follows: In Section 2, a literature review on the indicators for evaluating land use and the determination factors of mining intensity is outlined to propose a quantitative evaluation of the environmental impact of mining activities. Section 3 presents the methodology of comparative analysis between global warming issues and environmental impact of mining activities in the process of metal production and its effect on metal substitution. Section 4 illustrates the results of the comparative analysis and environmental impact due to the metal substitutes. The obtained results and the limitation of the assessment are discussed in Section 5. Finally, Section 6 presents the conclusions.

2. Prospective indicators for mining activity

Mining is a process of abiotic resource extraction and it affects the anthropogenic land use (Taelman et al., 2016). The proposed approaches for evaluating the overall land use and environmental systems are first surveyed, to develop an indicator appropriate for mining activities.

Many research works highlighted the potential impact of land use on the environmental system in the LCA narratives (Bare, 2010) from the perspectives of biodiversity (Koellner et al., 2013; Crenna et al., 2018; Fantke et al., 2016), chemical contamination (Koellner et al., 2013;