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Comparative life cycle assessment of tailings management and energy scenarios for a copper ore mine: A case study in Northern Norway

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ABSTRACT

In support of continuous environmental improvement in the mining industry, it is important to systematically assess the environmental impacts of mining and mineral processing operations from a life cycle perspective. Although life cycle assessment (LCA) is widely used as an environmental systems analysis tool, the application of LCA in the mining industry is still in progress. This paper carried out a cradle-to-gate LCA of an underground copper ore mine planned in Northern Norway. Based on the ReCiPe midpoint (hierarchist) life cycle impact assessment method, results of the study showed that on-site electricity use, diesel for mining trucks and blasting dominated contributions across six, four and four, respectively, of the eighteen categories assessed, and metals leaching from tailings were the primary contributors to the human toxicity and marine ecotoxicity impacts. Compared to the baseline, results of the energy-oriented scenario analysis indicated that electrification of diesel-driven mining trucks would be more environmentally beneficial as long as the electrical supply is “relatively clean” across impact categories. While electrodialytic tailings remediation could extract up to 64% of copper in tailings prior to disposal and significantly reduce the human toxicity impact of tailings, the marine ecotoxicity impact of tailings after electrodialysis changed inconsistently across the ReCiPe hierarchist and egalitarian perspectives. It is recommended to further assess the trade-off between the benefits of electrodialytic tailings remediation (extracting more copper) and the potential impacts of deposited tailings after electrodialysis from a multi-criteria decision-analysis perspective. In a generic context, this study provides an insight in further promoting LCA as an environmental decision-support tool, especially for comparing available cleaner production options, improving the overall environmental performance of a mine, and facilitating better communication with stakeholders.

1. Introduction

There has been a growing expectation on the mining and mineral processing industries to operate in a more responsible and sustainable manner, particularly on reducing the environmental impacts and improving resource management. The International Council on Mining and Metals (ICMM) has claimed that mining will be needed to meet the growing demand for minerals and metals, “even with society achieving greater efficiencies through reduction of extraneous uses, reuse, and recycling” (ICMM, 2012). The World Economic Forum (2014) has called for paying more attention to the environment aspects of the mining and mineral sector, due to (i) stricter environmental standards for greenhouse gas (GHG) emissions, energy and water consumption, waste management and biodiversity, and (ii) adaptation of mining operations to changing climate conditions. Regarding future mining challenges, the implications of declining ore grades, cradle-to-cradle management of all materials, and the inevitable shift from surface to massive underground mining have been emphasized (Moran et al., 2014). To support cleaner production and environmentally friendly decision-making in the mining industry, it is crucial to systematically assess resource-, energy- and tailings-related impacts from a life cycle perspective.

Life cycle assessment (LCA) is an internationally standardized method for assessing the potential environmental impacts associated with the whole life cycle of a product or service (ISO, 2006). In

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general, LCA results provide a more holistic understanding of the overall impacts of a mine and can contribute to continuous corporate environmental improvement. The last revised ISO 14001:2015, one of the world's most widely used environmental management standards, re-emphasized the importance of employing a life cycle perspective to better address emerging challenges of corporate environmental management with respect to sustainable resource use, energy & water use, climate change mitigation, and stakeholder-focused communication (ISO, 2015). Without LCA, environmental improvement measures of a mine may be ad-hoc and suboptimal (Awuah-Offei and Adekpedjou, 2011). However, the application of LCA in the mining and mineral sector is still in progress, partly due to a lack of publicly available operational data suitable for use in LCA (Durucan et al., 2006). In particular, there are very few published mining LCA studies with a systematic examination of the overall plant-level environmental impacts of mine operations, including mining, mineral processing and tailings disposal.

The ecological sustainability challenges faced by the mining industry, to a large extent, relate to environmental management at the corporate level (Botin, 2009). Owing to declining ore grades on average, increasing copper demand and climate change concerns, mitigation of energy-related environmental impacts is becoming more important in the energy-intensive mining industry. This holds true even for mining operations in remote Arctic regions, such as Northern Norway and Greenland, where there is a clear trend of an upsurge in mining activities in recent years (van Dam et al., 2014). In fact, the Arctic has experienced the greatest regional warming on earth since the 1950s, with an average annual temperature increase by 2–3 °C and in winter by up to 4 °C (Huntington et al., 2005). In support of reducing CO_2 emissions from copper production in Europe, the European Copper Institute has suggested four strategies in relation to energy efficiency, the use of renewable energy sources, appropriate technologies for mitigation, and electrification of equipment and transportation (ECI, 2014). Previous mining LCA studies in the literature have investigated the environmental impacts of energy-oriented scenarios, such as on comparing diesel-powered mining trucks with electric belt conveyors (Erkayaoğlu and Demirel, 2016), while most of them have not discussed in detail the relative contribution of alternative energy options to the overall environmental performance of a mine across impact categories.

Besides mitigation of energy-related environmental impacts, another (even more) important concern is tailings management at mine sites. Mine tailings, either stored on land or deposited in marine/riverine systems, may cause significant environmental problems. The high potential risk of mine tailings is largely due to heavy metals leaching from tailings storage facilities, related to acid mine drainage from conventional land-based tailings ponds and desorption from marine and riverine tailing placements. Although the mining and mineral extraction industry is of importance in society, however, leaching from tailings has been crudely defined in most mining LCA studies. There is not yet a widely accepted recommendation in the literature on how to define long-term leaching of metals from mine tailings in the life cycle inventory phase (Pettersen and Hertwich, 2008). The under-communicated potential environmental impacts of tailings in mining LCAs partly hinder the application of LCA in the mining industry, especially for supply of environmental information to support ecological sustainability-related communication among stakeholders.

In comparison with mine tailings disposal strategies of reuse, recycling and reprocessing (Edraki et al., 2014), we argue that a more proactive paradigm could be to extract more valuable metals from tailings before final disposal or re-use. One applicable method is electrodialytic remediation, which has been shown to extract up to 70% of metals present in mine tailings (Jensen et al., 2016). What remains unclear is whether there is a trade-off between mineral resource recovery (extracting more metals from tailings) and the environmental impacts of tailings after electrodialysis. To our knowledge, there is still no published LCA literature comparing the potential environmental impacts associated with direct tailings disposal and tailings after electrodialytic remediation.

In an attempt to address the above-mentioned gaps, this paper assessed the potential environmental impacts of an underground copper ore mine, located in northern Norway, planned to open in 2019. Firstly, environmental hotspots of the copper ore mine were identified at the plant level. Secondly, we compared the impacts of alternative energy options (diesel-driven vs. electric trucks, heavy fuel oil vs. natural gas) and tailings management scenarios (direct disposal vs. electrodialytic remediation prior to discharge), including their relative contributions to the overall impacts of the mine. Moreover, we employed sequential extraction to estimate the metal leaching potential of tailings and assessed the impacts of tailings from different ReCiPe perspectives. Results of this study could be used as a science-based foundation to aid in both internal discussions (e.g. on cleaner production measures and improving environmental management) and external communication with stakeholders and other copper mines (e.g. on benchmarking the impacts of mining operations) towards better environmental decision-making.

2. Application of LCA in mining and mineral processing

Since the 2000s, LCA has attracted considerable attention from the mining communities. As early as 2002, the Mining, Minerals and Sustainable Development (MMSD) Project report pointed out that "the mining and minerals industry has started to engage in the development of LCA as one element of a holistic approach to decision-making for sustainable development" (IIED, 2002). During the past years, efforts have been devoted to promoting the application of LCA in the mining and mineral sector. For example, Durucan et al. (2006) developed a mining life cycle model with an inventory database, enabling mining LCA studies to be conducted with vast amounts of operational data. Yellishetty et al. (2009) carried out a critical review of existing LCA methods in the minerals and metals sector, and discussed the methodological drawbacks in relation to abiotic resource depletion, land use impacts, open-loop recycling, and spatial and temporal differentiation in LCA. In a review of publications before 2010, Awuah-Offei and Adekpedjou (2011) found that there was limited mining application of LCA in the literature, partly due to a lack of LCA awareness in the mining industry. Recently, Santero and Hendry (2016) reported the progress on harmonization of LCA methodology for the metal and mining industry, with respect to system boundary, co-product and recycling allocation, and impact assessment categories.

So far, most published mining LCA studies focused on assessing the environmental impacts of mine operations and metal production, with varying goal and scope definitions as well as impact assessment categories. This can be seen, for instance, from copper-related mining LCA studies in the literature. Norgate et al. (2007) presented the cradle-to-gate life cycle impact assessment results of metal production (copper, nickel, aluminum, lead, zinc, steel, stainless steel and titanium) in Australia, focusing on global warming potential (GWP), acidification potential (AP), solid waste burden and gross energy requirement. In a study on energy and GHG impacts of mining and mineral processing operations in Australia, Norgate and Haque (2010) concluded that the largest contribution to GHG emissions was from crushing and grinding steps in the case of copper ore, which became loading and hauling for the mining and processing of iron ore and bauxite. Memary et al.