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A thermodynamic-based life cycle assessment of precious metal recycling out of waste printed circuit board through secondary copper smelting

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ABSTRACT

This study provides an environmental impact assessment of the black copper smelting route for the processing and recovery of copper and other valuable metals such as gold and silver from waste printed circuit boards (PCB). Thermodynamic based analysis was conducted to simulate the recycling process and a life cycle assessment was carried out to estimate and compare the environmental impact of the two scenarios: (1) recycling of precious metal out of waste PCBs through secondary copper smelting (Electronic Waste Processing, EWP); and (2) secondary copper recycling without adding electronic waste to the feed (SCR). The results of the study revealed that environmental impacts of using e-waste along with low-grade copper scrap in existing smelters to recover precious metals are dependent on the distance the material feed travels to the smelter and the means of electricity supplying the smelter. It is also found that the impact of the EWP scenario for climate change, freshwater eutrophication, and fossil depletion is significantly higher than those obtained from the SCR scenario and it is mainly because the metal and oxide dust in former scenario needs to be further refined to recover metals such as nickel, zinc and lead. The results also confirm that 10% cut in electricity usage in EWP scenario, has the higher environmental benefit in almost all dominant categories.

1. Introduction

Electronic waste (e-waste) is chemically and physically distinct from other forms of municipal or industrial waste; it contains both valuable and hazardous material that require special handling and recycling methods in avoiding environmental contamination and detrimental effects on human health. Recycling can recover reusable components and base metals, especially copper (Cu) and other precious metals. In 2006, the world's production of e-waste was estimated at 20–50 million tonnes per year (UNEP, 2007), representing 1–3% of the global municipal waste production of 1636 million tonnes per year (OECD, 2008). Cobbing (2008) calculated that computers, mobile telephones and television sets would contribute 5.5 million tonnes to the e-waste stream in 2010, rising to 9.8 million tonnes in 2015. In rich countries, e-waste constitutes around 8% of municipal waste by volume (Widmer et al., 2005). The chemical composition of e-waste differs subjected to the age and type of the waste item. However, most e-waste contained a mixture of metals, particularly Cu, aluminium (Al) and Iron (Fe), shielded with, or mixed with different types of plastics and ceramics

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(Hoffmann, 1992). An unwanted personal computer with a CRT monitor normally weighs 25 kg and composes of metal (43.7%), plastics (23.3%), electronic components (17.3%) and glass (15%) (Berkhout and Hertin, 2004). Heavy waste electronic items, such as washing machines and refrigerators, which mostly consist of steel, may have lower potential environmental pollutants than lighter electronic waste items, such as laptop computers, which may encompass high concentrations of flame retardants and heavy metals (Robinson, 2009). Nearly all electronic waste comprises some valued components or base materials, particularly Copper, Silver and Gold. A recent economic analysis conducted by (Ghodrat et al., 2016) confirmed the considerable potential value of e-waste recycling that should be taken into consideration. According to a survey carried out by Davis and Herat (2008) very limited audit data relating to the composition of e-waste within the domestic waste stream exists in Australia; also very few facilities can handle the processing or recycling of e-waste. This is further multiplied by large geographical distances between many of the major metropolises and the treatment spots. Davis and Herat (2007) hence concluded that e-waste reprocessing is only environmentally and economically viable in larger cities in Australia where demand is high. Lately a set of new legislation for the disposal and handling of e-waste in Australia developed using the European Union (EU) directive as a basis which takes into consideration factors unique to the Australian situation.

Basically the concentration of precious metals in waste PCBs is higher than the concentration of precious metals in their ores (Chancerel et al., 2009). Based on the research done by Hagelüken et al., (2005), currently mined ores for the extraction of gold and palladium include less than 10 g/t of precious metals compared to the concentrations of the similar metals in PCBs of personal computers (250 g/t of gold and of 110 g/t of palladium). On the other hand, the extraction of precious metals through mining is associated with negative environmental impacts through significant emissions of greenhouse gases and energy, water, and land usage (Ayres 1997). Additionally, the environmental impact of informal recycling of valuable metals out of e-waste especially in undeveloped countries could be critical and may lead to human health risk.

Based on the research conducted by (Morf et al., 2007) on the component concentrations from Swiss e-waste, it was revealed that concentrations of Cd, Cu, Ni, Pb and Zn released into the environment would pose a risk to the ecosystems (Widmer et al., 2005) and the potential hazards of persistent inorganic and organic contaminants (such as toxic PCBs, Polybrominated diphenyl ethers (PBDEs), and metals) to the ecosystem are expected to persist for many years. There is limited information, however, on the impact of e-waste processing through secondary metal scrap recycling on environmental and human health. In this regards, this paper aims to explore the environmental consequences of alternatives for recycling high-grade waste PCBs through black copper smelting route (a secondary copper production process). The motivation for this is to replace a portion of the secondary copper (low-grade copper scrap) with waste PCB scrap. This can further increase the utility of existing plants without the need to invest capital in new installations and at the same time, moves toward forming a close-loop for copper therefore the environmental consequences of replacing a proportion of secondary feed in existing smelters in Australia are also explored in this paper. Life cycle assessment (LCA) is an analytical tool for quantifying resource consumption and environmental impacts linked to a product, process or activity during its entire life cycle. The purpose of most LCA studies is to find the design option that minimises the life cycle impact of the process.

A substantial body of research on the life-cycle analysis of energy usage and environmental impacts of metals is available from various life cycle inventory (LCI) databases (Classen et al., 2009; Althaus and Classen, 2005, Althaus et al., 2007, Design, 2012). Yet, many LCI data are reported in an aggregated form and hence makes it challenging to make vigorous comparisons or taking co-production matters into account. A research carried out by Nuss and Eckelman (2014) overcome this issue to some extent by reviewing existing metals inventory data and collection of new data for several elements. Their results showed that for the majority of elements in their metallic form, the cradle-to-gate environmental burdens are largely a result of the purification and refining stages. On the other hand the criticality of different metals used in modern technologies is an area of growing interest. For example criticality of metals recycling as an environmental risk alleviating technique addressed in the work of Graedel et al. (2015) and the European Union report of the Ad hoc Working Group on defining critical raw materials (Commission, 2014). In an effort to bring enhanced rigor evaluation of metallic resource recycling, in this paper we have developed a thermodynamic based life cycle assessment to provide data on precious metal recycling out of e-waste through black copper smelting process. The novelty of the black copper smelting in this process is to utilise copper as the collector for valuable metals, such as gold and silver.

Several studies have analysed the environmental impact of electronic waste treatment through LCA (Niu et al., 2012; Hong et al., 2015; Biganzoli et al., 2015; Bigum et al., 2012; Xue et al., 2015; Rubin et al., 2014; Wäger et al., 2011). In spite of their scientific contributions, quantitative assessments of the environmental loads due to recovery of precious metals out of waste PCBs are not included in the calculation of the aforementioned studies. Inventory databases are also variable in terms of geography and uncertainties involved, hence accurate results for Australian case studies are difficult to obtain. On the other hand LCA involving waste electronic equipment have generally been carried out from a product life cycle (Andrae and Andersen, 2010), including an emphasis on different waste management alternatives (Mayers et al., 2005; Park et al., 2006). Hagelüken and Meskers (2009) assessed the savings in CO_2 emissions from the recycling of metals in e-waste based on measurements at the Umicore facility (Belgium) and saved CO_2 emissions from the avoided production of metals from virgin sources (data from Ecoinvent). The resource issues are however often related to iron; aluminium and copper e.g. (Mayers et al., 2005; Hischier et al., 2005) and often the LCA studies have not in any detail included the precious metals. The purpose of this study is to establish a life cycle inventories (LCIs) for the recycling and recovery of copper, gold and silver by an LCA approach and to evaluate the environmental impacts connected to the recovery of metals from high-grade waste electronic equipment (WEE). High-grade WEE is the richest on precious metals containing products from IT and telecommunications equipment such as high grade boards (green boards with gold corners on IC chips). In this regard, this paper aims to address the above-mentioned needs in identifying the key factors to improve e-waste treatment process in Australia, characterize and compare the recycling methods with and without adding e-waste to the feed of a secondary coper smelting process.