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Environmental impacts of a hydrometallurgical process for electronic waste treatment: A life cycle assessment case study

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ABSTRACT

The recovery of precious metals through hydrometallurgical techniques is one of the most active research areas on recovery of metals from electronic scraps. In this perspective, a pilot plant was designed for the treatment of small WEEE (Waste Electrical and Electronic Equipment) via hydrometallurgy. The process is based on two different leaching steps, in nitric acid and in aqua regia, followed by electrodeposition processes, to mainly recover copper, silver and gold. Two adsorption steps were also carried out to recover nickel and tin.

The goal of the present study is to assess the environmental impacts associated with the designed hydrometallurgical treatment of the small WEEE through Life Cycle Assessment (LCA) methodology. The approach considered is cradle-to-gate, i.e., from the collected WEEE entering the collection centre to the secondary metals obtained from the hydrometallurgical treatment.

Results obtained by SimaPro software and CML-IA method show that the nitric acid leaching contributes mostly to the impacts of the hydrometallurgical process (from 40% to 80%), followed by the adsorption steps. From an environmental perspective, the latter can still be improved at the design phase by increasing the lifetime of the sorbents.

1. Introduction

Management of Waste Electrical and Electronic Equipment (WEEE) has been documented as the world's rapidly growing waste stream which has the growth rate of 3–5% per year and potentially the biggest challenge to sustainability (Menikpura et al., 2014). Electronic waste has been indeed generated two to three times faster than other waste streams, due both to rapid increase in consumer electronic devices, and to their ever wider distribution (Ilyas et al., 2014). Only in Europe, each citizen produces about 17 kg of WEEE per year and, according to European Union estimates, this value is expected to rise to 24 kg by 2020 (EU, 2012). These solid wastes are usually dumped at landfills (Ilyas et al., 2014) even if they are rich in precious and strategic metals and, in many cases, are characterized by higher valuable metals contents than those of natural minerals. From this context a new approach/perspective has emerged: it is known as "urban mining", and bases on the development of best practices for collection, transportation, recycling and recovery of valuable metals from WEEE, so as to transform the waste into an economic valuable product and to minimize the consumption of resources. For these reasons, the study of a targeted and efficient recovery from WEEE can only lead to undeniable both socio-economic and environmental benefits (Iannicelli-Zubiani et al., 2012).

From a technological point of view, recycling of WEEE and recovering of metals therein contained can be divided into three major steps (Cui and Forssberg, 2003):

(1) Disassembly: operating a selective disassembly to single out hazardous or valuable components for special treatment;
(2) Upgrading: using mechanical and/or metallurgical processing to upgrade wanted materials content;
(3) Refining: recovered materials retreating or purifying by chemical processing so as to be acceptable for their original using. This final step can be realized by different

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metallurgical techniques: pyrometallurgical, biometallurgical, and hydrometallurgical.

Pyrometallurgical processing has become a traditional method to recover non-ferrous metals as well as precious metals from electronic waste in the past two decades. In the process, the crushed scraps are burned in a furnace or in a molten bath to remove plastics. However, most methods involving pyrometallurgical processing of electronic waste give rise to the following limits (Cui and Forssberg, 2003):

(1) Integrated smelters cannot recover aluminium and iron as metals;
(2) The presence of halogenated flame retardants (HFR) in the smelter feed can lead to the formation of dioxins unless special installations and measures are present;
(3) Ceramic components and glass in the e-waste increase the amount of slag from blast furnaces, which thereby increases the loss of precious metals and base metals from the scrap;
(4) Energy recovery and utilizing of organic constituents as reducing agents are only on its beginning;
(5) Only partial separation of metals can be achieved using pyrometallurgy, resulting in a limited upgrading of the metal value. Furthermore, hydrometallurgical techniques and/or electrochemical processing are subsequently necessary.

Regarding biometallurgical processing, recovery of metals by this method has been one of the most promising technologies and the understanding of the biochemical processes involved in the treatments of metals has been subjected to growing investigations in the last decade. At present, research and development are in progress for a number of rare earths, copper, nickel, cobalt, zinc, gold and silver. However, the advances obtained from the activity of leaching bacteria for recovery of gold and silver from ores are not those anticipated, due to the presence of elements toxic to the bacteria (Komnitsas and Pooley, 1991).

Anyway, the most active research area on recovery of metals from electronic scraps is recovering precious metals by hydrometallurgical techniques. Hydrometallurgical method has been indeed reported to be one of the most interesting, being generally applicable to very different compositions (Iannicelli-Zubiani et al., 2012). Furthermore, hydrometallurgical processes offer a promisingly eco-friendly and selective separation of the metals from the non-metallic parts (Fogarasi et al., 2013).

In this perspective, a pilot plant was designed for the treatment of small WEEE via hydrometallurgy. The process bases on two different leaching steps, in nitric acid and in aqua regia, followed by electrodeposition processes, to mainly obtain the recovery of copper and gold.

Since in some hydrometallurgical processes the use of high volumes of leaching solutions leads to the formation of large quantities of wastewater, it is important to assess the environmental impacts of the process and to exploit this information in scaling-up from the design phase to the realization of the pilot plant. For these reasons, it is necessary to make an environmental impact assessment of the designed processes before they can be applied at pilot or industrial scale. So the goal of the present study is to assess the environmental impacts by life cycle assessment (LCA) methodology associated with the hydrometallurgical treatment of WEEE, aimed at recovering precious metals. Furthermore, the present study is motivated by a lack in the LCA literature of a similar process. This methodology has been applied to the management of electronic waste, by assessing the potential environmental impacts derived from different treatments processes (Bigum et al., 2012; Hischier et al., 2005; Menikpura et al., 2014; Tan et al., 2015) and scenarios (Hischier, 2014). Only few studies have focused on hydrometallurgy (Rocchetti and Beolchini, 2014; Rocchetti et al., 2013; Rubin et al., 2014) even if more generic scraps are treated (i.e. fluorescent lamps, cathode ray tubes, Li-ion accumulators and PCBs) and different leaching agents are used (i.e. sulphuric acid and aqua regia).

2. Hydrometallurgical processes

The main steps in hydrometallurgical processing consist of a series of acid or caustic leaching steps of solid material. The solutions are then subjected to separation and purification procedures (such as precipitation of impurities, solvent extraction, adsorption, ion-exchange, electrorefining, chemical reduction or crystallization) to isolate and concentrate the metals of interest.

Among others, hydrometallurgy has been reported to be one of the most interesting being characterized, with respect to pyrometallurgy, by the following advantages:

(1) Reduced risk of highly toxic and polluting emissions, in particular the ones caused by the presence of halogenated flame retardants (HFR), which can lead to the formation of dioxins and furans;
(2) Efficient separation of metals avoiding purification steps (Cui and Zhang, 2008);
(3) Low energy requirement by the plants, where it is not necessary a source of organic fuel;
(4) No combustion residue currently sent to final disposal (landfill);
(5) No dust emission that can pose a risk to both the environment and the human health (Tuncuk et al., 2012).

On the other hand, some disadvantages of this process are:

(1) The need of many process steps;
(2) The consumption of large amounts of chemicals;
(3) The generation of large amounts of waste water.

The separation and recovery of precious metals can be realized by means of different unitary operations. In the various analysed studies, the recovery of gold, coming both from computer printed circuit boards (PCBs) and from mobile phones, is accomplished through: ion exchange resins, carbon adsorption, solvent extraction, electrolytic deposition, precipitation and cementation. Silver is generally recovered with ion exchange resins, with solvent extraction or with electrorefining. Regarding the copper, instead, the most common techniques for separation are crystallization, solvent extraction, precipitation and cementation.

Ion exchange resins are composed by a polymeric matrix in which ions are entrapped or encapsulated: these ions are available for ion exchange (Sabot and Maestro, 2000). The resins can be cationic (capable of exchanging cations) or anionic (capable of exchanging anions). There are numerous resins for ion exchange, most of which are polystyrene-based, typically crosslinked with divinylbenzene, to which are then added functional groups capable of capturing or releasing ions.

Recently, the use of adsorption onto solid sorbents is obtaining more and more attention because of its advantages of high recovery, short extraction time, high enrichment factor, low cost and low consumption of organic solvents over liquid-liquid extraction (Li et al., 2011). In particular, adsorption has become one of the alternative treatments (Rao et al., 2008), being a simple and potentially low cost process. Indeed, technical applicability and cost-effectiveness are the key factors in the selection of the treatment technology (Nurchi and Villaescusa, 2012). The most used sorbent