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Economic evaluation of an electrochemical process for the recovery of metals from electronic waste

Luis A. Diaz, Tedd E. Lister *

Biological and Chemical Processing Department, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 38415-3731, USA

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ABSTRACT

As the market of electronic devices continues to evolve, the waste stream generated from antiquated technology is increasingly view as an alternative to substitute primary sources of critical a value metals. Nevertheless, the sustainable recovery of materials can only be achieved by environmentally friendly processes that are economically competitive with the extraction from mineral ores. Hence, This paper presents the techno-economic assessment for a comprehensive process for the recovery of metals and critical materials from e-waste, which is based in an electrochemical recovery (ER) technology. Economic comparison is performed with the treatment of e-waste via smelting, which is currently the primary route for recycling metals from electronics. Results indicate that the electrochemical recovery process is a competitive alternative for the recovery of value from electronic waste when compared with the traditional black Cu smelting process. A significantly lower capital investment, 2.9 kg e-waste per dollar of capital investment, can be achieved with the ER process vs. 1.3 kg per dollar in the black Cu smelting process.

1. Introduction

The growing sales of small short-lived electronic devices is resulting in a significant stream of electronic scrap containing a wide variety of technology metals. These devices, which eventually become electronic waste (e-waste), are an important resource that could be leveraged to produce a sustainable supply chain for scarce and critical materials (Baldé et al., 2015; Dodson et al., 2012). The diversity of elements, in concentrations exceeding those found in mineral ores (Akcil et al., 2015), reveals an economic opportunity for the recovery of different value streams. Extensive research efforts are currently under development for the recovery of precious metals (Ag, Pd, and Au) and base metals (Cu, Sn, Pb, Ni, and Zn), for both economic and waste management purposes (Sun et al., 2015).

Small information technology (IT) waste, such as cell phones, personal computers, tablets, etc., is one of the six different e-waste categories, which is showing the most accelerated growth driven by changes in consumer habits and rapid technology developments (Geyer and Doctori Blass, 2010). Others e-waste categories are temperature exchange equipment, screens, lamps, large equipment, and small equipment (Baldé et al., 2015). Based on the data presented in the Global E-Waste Monitor 2014 (Baldé et al., 2015), it can be estimated that almost 707 kt of small IT e-waste were generated in the United States alone during 2014. In addition to precious and base metals, small IT waste contains low but significant quantities of materials that are considered critical for the renewable energy sector and the manufacturing of new IT products (DOE, 2011; Tukker, 2014). Rare earth elements (REE) such as Nd, Pr, Dy, and Gd, can be found and recovered from speakers, hard disk drives, and vibrators (Lister et al., 2014; Tukker, 2014). However, The compact design of the small IT waste makes it the most difficult e-waste category for recycling (Zeng and Li, 2016).

1.1. Current e-waste management technologies

Despite significant increases in the recycling of e-waste in the United States, which was estimated to increase from 37.8 to 41.7% between 2013 and 2014 (EPA, 2016), the majority of the e-waste is still retained by the end consumers and/or disposed in landfills. The development of an effective collection system would be necessary to assure a full advantage of the recoverable value of the e-waste (Geyer and Doctori Blass, 2010). For the recycled fraction, existing metal recovery technologies are based on pyrometallurgy, hydrometallurgy, or combinations of both process (Hagelüken, 2006a). Under western environmental standards

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* Corresponding author.
E-mail address: tedd.lister@inl.gov (T.E. Lister).

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smelting appears to be the primary recovery method employed (Cui and Zhang, 2008; Tuncuk et al., 2012). While currently performed primarily in large smelters in Europe and Asia, research continues to seek cleaner methods as presented in recent reviews on the subject (Cui and Zhang, 2008; Ghosh et al., 2015; Kaya, 2016). Modern smelters take advantage of the organic load (polymers) in the e-waste to reduce the consumption of coke as energy and reducing agent in the smelting process (Hagelüken, 2006a). Metals such as copper and lead are being recovered via pyrometallurgical routes, while hydrometallurgical processes are used at the back-end for the extraction and refining of precious metals (Hagelüken, 2006b). Umicore's integrated metals smelter and refinery plant in Belgium is one example of an operating Pb/Cu/Ni pyrometallurgical based process with a total capacity of 250 kt of feedstock that includes but is not limited to printed circuit boards and electronic components. This plant produces Au, Ag, platinum group metals (Pd, Pt, Rh, Ir, Ru), special metals (Se, Te, In), secondary metals (Sb, As, Bi), and base metals (Cu, Sn, Pb, Ni) as value streams (Hagelüken, 2006b; Khaliq et al., 2014).

Several challenges exist for the processing of e-waste in smelting facilities. Among them are high energy consumption, large capital costs, and hazardous emissions of dioxins generated from the presence of halogenated flame retardants in the e-waste (Hagelüken, 2006a; Khaliq et al., 2014). In order to comply with dioxin emission regulations, an additional capital investment is required for smelting facilities (Hagelüken, 2006a; Hagelüken, 2006b). Smelters that use feedstock composed of pyrite (FeS_2), such as the lead smelters, can significantly reduce dioxin emissions from e-waste (Mukherjee et al., 2016). However, the copper produced as matte in lead smelters steel needs to be refined through black copper smelting (Khaliq et al., 2014). This problem limits processing of electronic waste to existing smelters. Therefore, large scale operation plants are required for the financial sustainability of the pyrometallurgical process (Ghodrat et al., 2016; Hagelüken, 2006a).

Hydrometallurgical processes are often described as a cleaner and less expensive alternative to pyrometallurgy, which can be implemented at smaller scales (Tuncuk et al., 2012). However, high operational costs and a significant environmental impact come as a result of the slow processing rates, high liquid to solid ratio (ratio of leaching solution to solid waste), and extensive use of chemicals. These problems are caused by the complex elemental distribution of metals in the e-waste where over 80% of the total recovery value is held in the precious metals, which are less than 1% of the total metal content (Diaz et al., 2016; Vats and Singh, 2015). Thereby, the hydrometallurgical processing of e-waste requires extensive consumption of chemicals for the removal of the less noble metal content, which are higher in quantity but have limited contribution to the total recoverable value (Diaz et al., 2016). Moreover, the presence of metals like copper, which consume the oxidants required for the extraction of precious metals, makes necessary the removal of such metals before the precious metals extraction (Torres and Lapidus, 2016).

1.2. Electro-recycling (ER) as alternative process

In order to address some of previously mentioned issues associated with the current metal recovery processes, an electrochemical-hydrometallurgical mediated approach has been proposed by (Diaz et al., 2016; Lister et al., 2014). In the (ER) process a weak oxidant (Fe^{3+}), is continuously regenerated at the anode of an electrochemical cell (Eq. (1)), and used for the extraction of base metals in an external extraction column (Eq. (2)) (Lister et al., 2014). The solution with the reduced oxidant and the leached metals is then returned to the cathode side of the electrochemical cell, where the leached metals are recovered (Eq. (3)). A more detailed description of the ER process can be found elsewhere (Diaz et al., 2017; Diaz et al., 2016; Lister et al., 2016; Nguyen et al., 2017). The ER technology has been developed as an alternative to reduce chemical consumption and enrich the e-waste material for the further extraction and recovery of precious metals. In a comprehensive approach, with the addition of physical separation steps, REE can also be recovered as a separated value stream (Diaz et al., 2016).

$$Fe^{2+} \rightarrow Fe^{3+} + e^- \quad E^0 = 0.771\ \text{V vs. SHE} \tag{1}$$

$$nFe^{3+} + M \rightarrow M^{n+} + nFe^{2+} \tag{2}$$

$$M^{n+} + ne^- \rightarrow M \tag{3}$$

Although the technical viability of the ER process has been demonstrated, an economic analysis is necessary, in every development stage, to assess the economic feasibility as the main factor to determine the project continuation and to establish performance targets. In the early stage, there are several factors that that could affect the project financial behavior, which cannot be known with any certainty. Therefore, one of the best ways to evaluate early development technologies is by comparison with competing processes or alternatives (Smith, 2005). For the processing of e-waste, the pyrometallurgical route has being identified as the alternative technology for which the ER process would need to demonstrate economic competitiveness in order to be implemented.

While detailed data on operating smelters is not widely available, limited data exists on the process economics of smelting electronics with copper. Ghodrat et al. recently presented a techno-economic analysis (TEA) for black copper smelting (BCS) using e-waste as co-feedstock (Ghodrat et al., 2016). In this work, the authors demonstrated that the economic viability of the process is mostly affected by the cost of the e-waste along with process capacity. The minimum viable smelting operation requires an annual throughput of 30 kt/year (48% of which corresponds to e-waste). For the TEA, the mass and energy balances were completely supported on thermodynamic calculations. A second paper, by the same research group, extended the information on the thermodynamic analysis for the processing of e-waste through the BCS route (Ghodrat et al., 2017).

In order to evaluate the economic feasibility of the ER process, this paper presents a TEA and a comparison of the value recovery from e-waste through the ER and BCS routes. A base scenario of 20 kt/year of cell phone material is considered to assess the processing of small IT waste. Sensitivity analyses are used to account for the effect of plant size, TEA assumptions, and uncertainties such as operational costs and precious metals recovery efficiencies. A brief description of the extraction steps of the process is presented, as well as the analysis of the ER process effect on operational costs and economic feasibility of the process.

2. Methodology

Process flow diagrams (Figs. 1 and 2 for Cu smelting and ER process, respectively) were established for comprehensive e-waste processing that includes comminution, separation, and the recovery of value streams of metals and critical materials (including REEs) from scrap mobile electronics. Mass and energy balances for the BCS route were based on the information presented by Ghodrat et al. (2016, 2017), but adjusted to the composition of cell phone waste presented in Diaz et al. (2016). Mass and energy balances for the ER process were obtained from experimental data reported elsewhere (Diaz et al., 2017, 2016). A brief description of the BCS route and the ER process is presented below. The REE extraction and recovery route, which is identical for both processing routes is also described.

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