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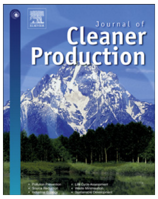

Recycling of metals from urban mines – a strategic evaluation

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ABSTRACT

Urban mining has attracted increasing attention as a research topic, owing to the high growth rate, environmental issues, and market potential of waste generated in urban areas. Metal recovery from such waste has become increasingly important especially in accordance with the concept of metal criticality. This study develops a model by evaluating various types of urban waste in order to understand the criticality of these waste streams and determine their potential for metal recovery. Two factors, i.e. the resource index and technology index, are defined and assessed through a systematic review of data from the literature and industry. High values of the resource index indicate that the waste is important to the European Union (EU) economy and hence has significant potential for recycling as a resource. Furthermore, a high technology index indicates that the waste can be processed for metal recovery with less technology investment than that required for a waste that has a low technology index. However, a high environmental impact for the recovery of metals, indicates that processing of the waste is difficult and potentially has high impact on the environment. A case study of 11 waste streams from a local recycling company is performed, by using the correlation of these two indices. The results of the evaluation suggest that the information and communication technology (ICT) scrap and the rare-earth elements (REEs) containing end-of-life (EOL) products exhibit significant potential for metals recovery. The technical aspects governing the recovery of valuable metals from these two resources are further analysed and potential processing routes (flowsheets) can be suggested. Combined with both physical separation and metallurgical processing, the proposed evaluation methodology and the processing routes for targeted critical metals, are expected to contribute to the development of competitive recycling technologies.

1. Introduction

The scarcity of materials, which is largely driven by global population growth and increased consumption especially in the high-tech industrial sectors (Wouters and Bol, 2009) has become a critical global issue in recent years. This issue stems from the fact that the primary raw minerals are usually non-renewable. After extraction and usage, many elements are relegated to the "urban mine" (waste), in the form of end of life (EOL) products (Kiddee et al., 2013). The "urban mines" considered in the current work include secondary resources that are directly generated from urban areas; however, industrial waste such as red mud, BF/BOF slag, etc. are not considered. Attempts to tackle the scarcity of materials and thereby ensure their sustainability, have focused on steering the life cycles of valuable elements away from such waste. The primary goal of this strategy is to achieve maximum materials utilization at minimum production and processing costs and with low overall environmental impact (Allwood et al., 2011). However, the quality of primary raw materials is continuously decreasing, i.e. the concentration of targeted minerals in the ore is decreasing and the impurity levels are increasing. As such, current primary mining processes undergo continuous development to process the often varying and decreased grade of raw materials feed (Kleijn, 2012); this development leads to significant narrowing of the profit margin. Modern industries have, in fact, adopted a responsible and environmentally sound development path that is based on a long-term innovative and sustainable strategy (Wouters and Bol, 2009). Ensuring both the quality and quantity of raw material supplies is (and will be) an important issue, which drives, at least partially, current industrial research and development of alternative technology.

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"Urban mines" from various types of waste streams are readily accessible and consist of significant concentrations of valuable metals, such as waste electrical and electronic equipment (WEEE, or e-waste). However, the inefficient use of these mines (Cui and Zhang, 2008) has led to increased imbalance between the shortage of, and the high demand for, metals. Moreover, owing to the increasing importance of metal criticality (DOE, 2010; Moss et al., 2011), metal recycling from "urban mines" has become essential (Agrawal et al., 2009; Allwood et al., 2011; Cui and Zhang, 2008; Kiddee et al., 2013; Moss et al., 2011; Robinson, 2009; Tanskanen, 2013). In the EU, critical raw materials (i.e. mostly metals) are considered fundamental to the EU economy and hence essential for the development and stability of each society. In 2013, 20 critical raw materials, mostly metals, were selected from 54 non-energy and non-food materials, based on the Oakdene and Fraunhofer report (Chapman et al., 2013).

Different types of waste are generated from various sources, such as households and industrial sites or offices (Lundgren, 2012). The methods for collection and treatment of waste vary with the type and location of the waste stream. In addition, these methods depend on (for example) the quality or value of the waste, local legislation, infrastructure, and the availability of effective technologies. The main activities in the metals recycling industry typically consist of waste collection and transport, dismantling and size reduction, sorting and physical separation, and further smelting and refining (Hageluken, 2005). Although many waste streams are accessible through urban mining, industry and policy makers have found it increasingly difficult to determine the importance of a given waste stream; the realisation of sustainable and profitable recycling from a pool of waste streams is especially challenging. A strategy that incorporates smart waste processing for the supply of materials from a variety of (waste) streams, is vital to the recycling industry. Several methodologies have been used to determine the 'metal/mineral criticality' (Chapman et al., 2013; Graedel et al., 2012, 2015). These methodologies cannot be used, however, to evaluate the importance/criticality of a specific waste stream. As such, the goal of this work is to present i) a straightforward methodology through which promising secondary resources (waste streams) can be efficiently identified, by taking the metal/mineral criticality into consideration (Chapman et al., 2013; Graedel et al., 2015) and ii) evaluations of metal recycling technologies, based on a critical literature review and a case study of samples obtained from a recycling company – the Van Gansewinkel Groep (VGG).

2. Evaluation of various secondary resources for metal recovery

2.1. *Impact of potential secondary resources for metal recovery on the market*

Urban areas consist of a wide range of secondary resources that are viable for metal recovery; the focus of the market depends significantly on the quantity and metal content of, as well as the efficiency of metal recovery from, the waste. The WEEE, waste magnets, spent batteries, spent catalysts, and residues from incineration of the MSW are among the most important secondary resources for metal recovery (DOE, 2010; EU, 2012). Without proper management of, or effective metal recovery from these resources, significant economic and environmental burdens can be induced by landfilling. In the EU, ~10 million tons of WEEE are generated annually (Khaliq et al., 2014). The collection and treatment of this WEEE has allowed an additional yearly and continually increasing investment of more than 10 billion euros, in the EU27 region (UNU, 2007).

Recovery of metals from these secondary resources is usually based on the fundamentals of metallurgy and the process design is tailored for each type of waste. These processes must be economically viable and industrially applicable, and the significance accorded to the treatment of each resource should take the environmental impact and the process availability into consideration. In addition, the costs associated with, and the revenues generated from the process are two of the main factors that determine the amount of research conducted and the level of industrial investment. For example, if the costs associated with metal recovery are substantially higher than those of the traditional natural mineral process, then the industrial implementation of the technology required for this recovery is typically delayed. This delay is effected even for new processes, whose environmental impact will be both positive and significant. The value of a waste stream plays therefore a potentially significant role in determining whether metal recovery processes should be performed. A comparison (Table 1) of the typical secondary resources (i.e. sources for metal recovery) available on the market, reveals significant inter- and intra-group variation in the metal content of the waste streams. MSW incineration residues typically have lower metal content than other waste streams in the urban areas. However, these residues occur in large quantities from which substantial metal recovery is realised. Many of the electronic waste streams contain relatively high concentrations of precious metals. Nowadays, these streams constitute one of the most important sources of precious metals, compared with the natural minerals (Hageluken, 2005; Li and Xu, 2011), although they can be less valuable than other streams (Fig. 1). Therefore, the recycling potential of a specific waste stream is characterized by several complex features. An understanding of these features and their dependence on various factors is crucial to determining the importance of a specific waste stream and its potential for metal recycling.

2.2. *Methodology development for selection of industrially viable secondary resources for metal recovery*

Although the market values of secondary resources are helpful in determining the importance of each resource, additional factors influence the industrial practice when a specific waste is considered. For example, the lead acid battery is one of the best recycled EOL products, while its market value is relatively low. A methodology that couples various components is therefore developed, as shown in Fig. 2.

This method will be used to evaluate the importance of a secondary resource for metal recycling and two major indices, i.e. the resource index and the technology index, are defined. These definitions are based on a systematic review of the characteristics of different resources and models describing the metal criticality, as reported in the literature (DOE, 2010; EU, 2012; Huang et al., 2009; Montero et al., 2012; UNU, 2007). A detailed description of the factors is given below.

2.2.1. *Resource index*

Identifying the factors that influence the role of a secondary resource in the market is essential. These factors include, in general, the type of constituent metals, the resource value, the importance of the resource to society, and the sustainability of the "supply". Nowadays, the supply of a waste stream or secondary resource depends significantly on the local policies and collection rules, infrastructure, and public awareness (EU, 2011, 2012; UNU, 2007; Žičkienė et al., 2005). The sustainability of this supply is difficult to determine, however, even when only the EU region is considered. As such, the risks associated with the supply of a waste stream are correlated to the supply risks of those constituent metals. This