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Electronic waste as a secondary source of critical metals: Management and recovery technologies

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ABSTRACT

The wealth of the society depends on several metals, including base metals, precious metals and increasingly rare earth elements (REE). They are collectively termed as technology metals. Numerous applications stimulated the use of technology metals, and their supply is at stake, owing to the high demand and uneven geographical distribution of these metals. Their stable supply is crucial for the transition to a sustainable and circular economy. There is an increasing interest in secondary sources of these metals. This article outlines the global state of electronic waste, its management and the latest technological developments in metal recovery from various streams of electronic waste. An emphasis is given to printed circuit boards (PCB), hard disc drives (HDD) and displays regarding their critical metal content. Physical, pyrometallurgical and (bio)hydrometallurgical metal recovery technologies are overviewed. In addition, perspectives on electronic waste as a secondary source of critical metals are given.

1. Introduction

1.1. Definition of electronic waste

Electronic waste refers to discarded electrical and electronic equipment that is at the end of its economic life span and no longer used by consumers. It is commonly shortened as e-waste, and referred to as Waste Electric and Electronic Equipment (WEEE). The WEEE Directive of the European Commission (2012/19/EU) grouped all WEEE into 10 primary categories. These 10 major product groups are classified per product type and legislative relevancy category. They are broken down into 58 sub-categories, approximately 900 products, in which all discarded devices are represented. They are also linked to 5–7 collection categories, which exists in actual WEEE practice (Wang et al., 2012b).

1.2. Generation of WEEE

Generation of WEEE is associated to rapid technological innovations and coupled to the demand growth in the electronics sector. In addition, decreasing economic lifespan of electronic devices (Zhang et al., 2012c), lack of international consensus on WEEE management (Friege, 2012), and inadequate user awareness play a role in the unprecedented increase of WEEE generation. In the period 2000–2010, the lifespan of electrical and electronic devices decreased from an average of 8 years to 2 years for large electrical and electronic equipment (EEE) and from 4 years to 9 months for mobile phone (Kasper et al., 2011; Zhang et al., 2012c). Electrical and electronic equipment (EEE) demand increased considerably in line with the economic growth particularly in developing countries (Zeng et al., 2015). These issues, coupled to an increasing spectrum of devices, exacerbate the global WEEE generation issue.

The quantification of WEEE volumes is challenging owing to the lack of appropriate waste tracking systems. Challenges include the lack of data accuracy concerning the collection and treatment of WEEE, as well as the dynamic behavior of the waste flows and their constituents (Schluep et al., 2013). WEEE quantification is particularly cumbersome in developing countries as informal waste management systems are poorly documented (Wang et al., 2013). There is a strong correlation between gross domestic product (GDP) and WEEE generation, and the economic development of a country is proportional with the amount of WEEE generated per person (Huisman, 2010). Thus, a sharp increase of WEEE generation in virtually all developing countries is expected in the coming decades.

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Table 1
Global growth of WEEE (Sources: Schluep et al., 2013; Ilyas and Lee, 2014b; StEP, 2016).

Country	EEE put on market in 2012 (10^6 tons)	Annual estimated WEEE in 2013 (10^6 tons)	WEEE per inhabitant (kg/person)	Estimated WEEE in 2020	Increase between 2013 and 2020
EU-28	9800	10205	19.6	11430	12%
United States	9350	9359	29.3	10050	7%
China	12405	6033	4.4	12066	98%
Japan	3300	3022	23.8	3200	5%
India	3026	2751	2.2	6755	145%
Germany	1752	1696	21.9	1974	16%
Russia	1599	1556	10.9	2000	28%
Brazil	1850	1530	7.1	1850	20%
France	1520	1224	21.6	1625	32%
Italy	1124	1154	19.3	1343	16%
Korea	959	961.3	19.2	1050	9%
Turkey	726	661	8.8	800	21%
Netherlands	432	394	23.3	421	6%
Romania	217	157	7.9	227	44%
Norway	175	127	25.8	136	7%
Bulgaria	86	62	8.6	89	43%

1.3. Global and regional WEEE generation

WEEE is the fastest-growing type of solid waste, occupying an increasing fraction of the global municipal waste (Kiddee et al., 2013). Global WEEE generation reached 41.8 million tons in 2014, and is forecasted to rise to 50 million tons in 2018 (Baldé et al., 2015). An overview of EEE put on the market, WEEE generation, and their projections until 2020 per country is given in Table 1 (Schluep et al., 2009; Ilyas and Lee, 2014a; StEP, 2016). The exponential increase in WEEE generation is particularly prevalent in countries with developed economies, in which EEE markets are saturated. In developed countries, WEEE makes up to 8% of the municipal waste by weight (Robinson, 2009), with an increasing relative fraction.

China plays a key role in the global EEE industry, in the manufacturing, the refurbishment, and reuse of EEE and recycling of WEEE. An increase in EEE usage and consequent WEEE generation is expected in China, and in other developing economies such as Brazil, Russia, India as well as Turkey and South Africa (Schluep et al., 2009). In the coming years, China will become the major WEEE generator, next to its status as a primary EEE producer (Wang et al., 2013).

1.4. Electronic waste as a secondary source of metals

The perspective in solid waste management has shifted in the last decade from semi-engineered landfill disposal to recovery of materials and energy from secondary resources. In a circular zero-waste economy, material flows are closed by the recycling of discarded products and urban mining of current and future waste streams (Jones et al., 2013). Waste materials that are reprocessed to generate raw materials, potentially substituting the use of primary materials, are regarded as secondary raw materials (Ongondo et al., 2015).

Use of secondary raw materials for resource recovery allows the conservation of primary ores, thus significantly reducing the carbon and ecological footprints (Tuncuk et al., 2012). Additionally, up to 95% and 85% energy is saved when recycling, respectively, aluminum (Al) and copper (Cu) compared to the production from primary ores (Cui and Forssberg, 2003). Currently, 50% of the semi-finished copper products come from recycled materials (Schlesinger et al., 2011).

In addition to all the hazards originating from WEEE, manufacturing of mobile phones and personal computers consumes considerable fractions of the gold (Au), silver (Ag) and palladium (Pd) mined annually worldwide (Hadi et al., 2015). The electronics industry is the third largest consumer of Au, accounting for 12% of the total Au demand (about 282 tons) in 2014 (Schipper and de Haan, 2015). Worldwide, more than one million people in 26 countries across Africa, Asia and South America work in Au mining mostly in unregistered substandard conditions (Mccann and Wittmann, 2015), driven by the demand of this precious metal for electronics.

An illustrative explanation of the role of landfill mining, recycling and urban mining is given in Fig. 1. The reintegration of wastes and by-products back in the economy strongly relies on the concept of waste as a secondary raw material (Jones et al., 2013). In urban mining of end-of-life (EOL) devices, WEEE is a primary target owing to its high content of valuable critical metals. In addition to being a hazardous waste, WEEE is an important secondary source of metals in the transition to a circular economy.

Several technical and non-technical tools have been developed to manage WEEE sustainably, taking a holistic approach that encompasses the entire chain of WEEE management, including collection, pretreatment, recovery and final disposal (Kiddee et al., 2013). Distinctive to primary mines, most secondary raw materials are rich in complex mixtures of metals, multi-element alloys, and polymetallic structures (Tuncuk et al., 2012; Ongondo et al., 2015). The complexity of WEEE increased with the development of technology as the production of electronic devices relies on a great number of elements. Modern devices consist of up to 60 elements in various mixtures of metals (Bloodworth,

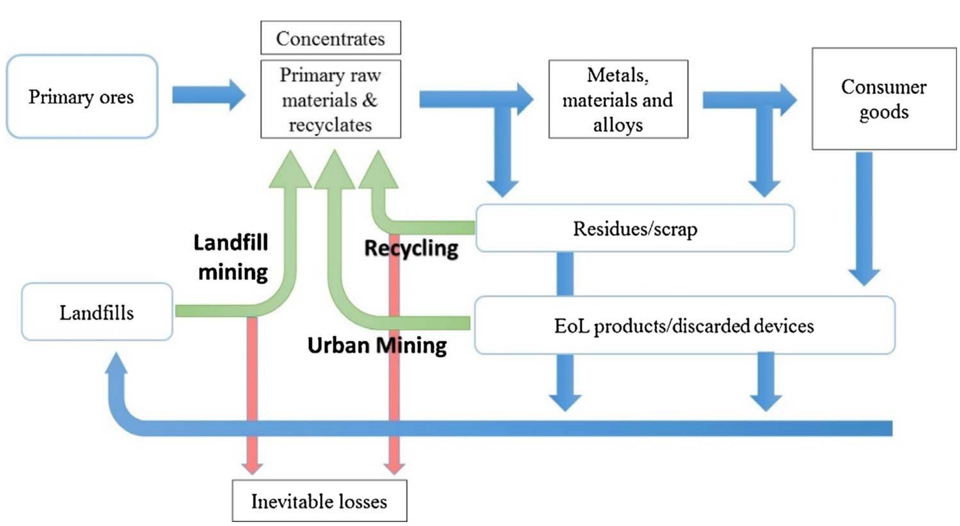

Fig. 1. Closing material loops in a circular economy (EoL: End-of-life devices) (Reproduced from Jones et al., 2013).