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Improving urban mining practices for optimal recovery of resources from e-waste

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ABSTRACT

In this article, current progress in urban mining related to e-waste recycling is reviewed and associated state-of-the-art recycling technologies are evaluated. As sufficient volume of e-waste is a limiting factor for its recycling economy, the need for the establishment of effective e-waste collection mechanisms, particularly for small sized End-of-Life (EoL) devices, is emphasized in terms of the need for effective government policies, increased public awareness, economic incentives, establishing industry-funded co-regulatory agreements, etc. Feasible options for e-waste recycling through pyro- and hydro-metallurgical process routes are reviewed. Deficiencies in e-waste recycling chains are highlighted, and recommendations to improve the current very low collection rate of small sized EoL devices such as mobile phones are made. Optimization of the recovery of the critical metals and energy through different processing options is discussed.

1. Introduction

Manufacturing of recyclable products and efficient recovery of resources such as chemicals, materials, and energy from waste streams are the key enablers of the circular economy. In this framework, the EU aims to be able to recycle 65% of its municipal waste by 2030 (European Commission, 2015). In order to facilitate this move, besides designing recyclable products, planning effective waste collection mechanisms and developing innovative recycling technologies are essential.

Today, increasing metals demand, the scarcity of primary resources and earth's intrinsic limitations pose a challenge to the valuable metals production system. In order to supplement scarce natural resources, urban mining such as the recovery of critical metals from waste of electronic and electrical equipment (WEEE) through sustainable recycling processes is evolving. The United Nations Environment Program (UNEP) is also calling for an urgent re-think of metals recycling practices as global demand for these critical metals continues to soar. The sustainable recycling practices enhance the critical metals production while managing environmental issues related to hazardous waste and emissions. Therefore, improvements in waste collection, treatment, and recycling in an energy efficient and environmentally friendly manner contribute both to a healthy economy and environment. Fig. 1 shows integrated urban mining at the core of a circular economy model that closes the metals loop, recovers energy, and manages environmental issues related to hazardous materials from the WEEE.

WEEE represents one of the largest sources of waste in the world with the highest growth rate per year (Cucchiella et al., 2015; Tuncuk et al., 2012). The recovery of precious metals and energy from these products therefore represents a significant economic opportunity. However, current recycling technologies and business models have limited ability to recover these resources, and associated recovery rates remain relatively low (Cucchiella et al., 2015). In order to address the scarcity of the critical metals' primary resources and environmental issues, developing innovative technologies, and business strategies for processing complex feed materials from e-waste streams in more energy efficient and environmentally friendly manner is essential.

In this article, current progress in urban mining is reviewed and the associated major metals recycling technologies are evaluated. The need for the establishment of effective End-of-Life (EoL) electrical and electronic equipment (EEE) collection mechanisms is highlighted in terms of government policies, increased public awareness, economic incentives, and installation of separate collection facilities at public places. Main features of the hydro- and pyro-metallurgical process routes including their advantages and disadvantages are evaluated. Recommendations to optimize the recovery of the critical metals and energy are discussed in detail.

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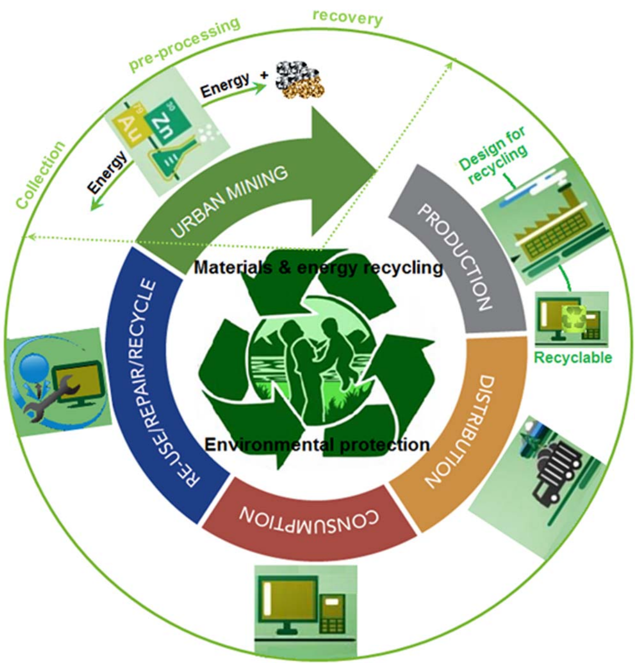

Fig. 1. Schematic diagram for an ideal circular economy model that closes the metals loop, recovers energy, and contributes to the environmental protection.

1.1. E-waste

The production of EEE is one of the fastest growing domains of the manufacturing industry globally. In response to the fast advancement in technology, the demand for EEE has increased dramatically. The high diversity of EEE coupled with a rapid obsolescence of products, due to advancement in technology that lead to continuous supply of devices with better features, and an increasing level of household equipment have led to an exponential increase in e-waste (Research and Markets, 2015). The EU WEEE directive classifies e-waste as electrical or electronic equipment which is discarded including all components which are part of the product at the time of discarding (European Parliament, 2003; BIO Intelligence Service, 2013). The EU WEEE directive categorizes e-waste into ten different classes from large household appliances to automatic dispensers. Currently, between $2.72 \cdot 10^7$ and $4.54 \cdot 10^7$ tonnes of e-waste per year is generated globally with major share from USA, China, EU, and Australasia, and this number is rising by about 3–5% annually (Cucchiella et al., 2015; UNU, 2017). Recently, UN reported that United Kingdom (UK), United States of America (USA), EU, and China generated about $1.18 \cdot 10^6$, $0.91 \cdot 10^7$, $1.00 \cdot 10^7$, and $1.00 \cdot 10^7$ tonnes of e-waste in 2012, respectively (Research and Markets, 2015; UNU, 2017). UN also estimated the global volume of e-waste in 2012 to have been $4.54 \cdot 10^7$ tonnes (Research and Markets, 2015), of which USA and China contributed for 32% of the total (UNU, 2017). In EU e-waste has been projected to increase by 45% between 1995 and 2020 (European Parliament, 2003).

Driven by rising incomes and high demand for new gadgets and appliances, countries in the Emerging Market Economies such as China and India are expected to become significant e-waste producers in the next decade (Robinson, 2009). A new UNU (UNU, 2017) research shows that the average increase in e-waste across 12 East and South-East Asian countries, including China, between 2010 and 2015 was 63% ($\sim 7.71 \cdot 10^6$ tonnes), with a total of $1.18 \cdot 10^7$ tonnes of e-waste, which is 2.4 times the weight of the Great Pyramid of Giza.

E-waste has a complex composition of ferrous, non-ferrous, plastic and ceramic materials. It is characterized by its significant amount of valuable metals. The presence of valuable metals in e-waste such as Au, Ag, Pt, Ga, Pd, Ta, Te, Ge, and Se makes it attractive for recycling. Based on an economic assessment made on selected 14 EEE in EU, Au has been found to have the highest recycling economic value (Cucchiella et al., 2015). In 2014, the study also suggested that the potential revenue that could be achieved from efficient recycling of the generated WEEE from the selected 14 EEE (LCD notebooks, LED notebooks, CRTTVs, LCDTVs, LEDTVs, CRT monitors, LCD monitors, LED monitors, cellphones, smart phones, PV panels, HDDs, SSDs and tablets) in EU alone to be €2.15 billion, and in future with increasing volumes of mobile phones, CRT monitors, and LCD notebooks the revenue may rise to €3.67 billion. Smart phones, mobile phones, CRT monitors, and LCD notebooks and TVs represent the e-waste streams with the greatest economic recovery value (Cucchiella et al., 2015). However, as e-waste is also classified as hazardous material, it should be handled properly. After collection, the e-waste has to be transported to disassembling plants where materials separation and sorting processes are conducted. This process includes removal of hazardous substances (Nowakowski, 2017).

Recovering materials from e-waste is more profitable than processing primary raw materials largely due to the energy efficiency associated with e-waste recycling. According to Boliden Rönnskär (Skelleftehamn, Sweden), extracting metals from e-waste requires only from 10 to 15% of the total energy required in metals extraction from ore concentrates. According to the Commodities Research Unit of UK report in 2011, EU is globally the leading e-waste recycler with a rate of 35% per year, e-waste recycling rate of USA is 27% per year (Namias, 2013).

1.1.1. Classification and composition of e-waste

According to the Association of Plastics Manufacturers in EU (APME), average materials consumption in EEE are 38 wt% ferrous, 28 wt% non-ferrous, 19 wt% plastics, 4 wt% glass, 1 wt% wood, and 10 wt% others (APME, 1995). The United Nations University (UNU, 2017) reported that the electronic industry consumes about 290.30 tonnes of Au and 6803.89 tonnes of Ag every year. Thus, despite its common classification as a waste, e-waste constitutes considerable amounts of secondary resource. As shown in Table 1, the average grades of Cu, Au, Ag, and Pd in e-waste are significantly higher than those grades in mined ores.

Metals in e-waste can be grouped into five major categories as described in Table 2. The extraction of precious metals, platinum group metals, and base metals from e-waste is a major economic drive due to their associated value. Printed circuit boards (PCBs) are the most *precious* part in e-waste streams. PCBs are found in electrical and electronics appliances such as TVs, computers and mobile phones. For example, flat screens contain one or more PCBs equipped with electronic components and connectors. Considerable amounts of precious metals are contained both in the components and connectors as well as in the solders (Buchert et al., 2012). For example, PCB from an LCD TV constitutes 575 mg of Ag, 138 mg of Au, and 44 mg of Pd (Buchert et al., 2012). In general, precious metals in PCB account for more than 80% of the total intrinsic value even though their composition in e-waste is less than 1 wt% (Park and Fray, 2009). PCBs are also embedded into other

Table 1
Weight distribution of PMs, PGMs, and BMs in e-waste (Kumar et al., 2017; Hagelüken, 2006).

E-waste	Fe (wt %)	Al (wt %)	Cu (wt %)	Plastics (wt%)	Ag (ppm)	Au (ppm)	Pd (ppm)
TV-board	28	10	10	28	280	20	10
PC board	7	5	20	23	1000	250	110
Mobile phone	5	1	13	56	3500	340	130
Portable audio	23	1	21	47	150	10	4
DVD-player	62	2	5	24	115	15	4
Calculator	4	5	3	61	260	50	5
Average EEE	–	–	13.8	–	1009	127	51.6
Ore/mine	–	–	0.6	–	215.5	1.01	2.7

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