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Review

Present status of the recycling of waste electrical and electronic equipment in Korea

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Abstract

In Korea due to rapid economical growth followed by urbanisation, breakage of large traditional families into small nuclear families, continuous changes in equipment features and capabilities causes tremendous increase in sale of new electrical and electronic equipment (EEE) and decrease in sale of used EEE. Subsequently, the ever-increasing quantity of waste electrical and electronic equipment (WEEE) has become a serious social problem and threat to the environment. Therefore, the gradual increase in the generation of WEEE intensifies the interest for recycling to conserve the resources and protect the environment. In view of the above, a review has been made related to the present status of the recycling of waste electrical and electronic equipment in Korea. This paper describes the present status of generation and recycling of waste electrical and electronic equipment, namely TVs, refrigerators, washing machines, air conditioners, personal computers and mobile phones in Korea. The commercial processes and the status of developing new technologies for the recycling of metallic values from waste printed circuit boards (PCBs) is also described briefly. Since 1998, three recycling centers are in full operation to recycle WEEE such as refrigerators, washing machines and air conditioners, having the total capacity of 880,000 units/year. All waste TVs are recently recycled on commission basis by several private recycling plants. The recycling of waste personal computers and mobile phones is insignificant in comparison with the amount of estimated obsolete those. Korea has adopted and enforced the extended producer responsibility (EPR) system. Korea is making consistent efforts to improve the recycling rate to the standards indicated in the EU directives

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for WEEE. Especially environmentally friendly and energy-saving technologies are being developed to recycle metal values from PCBs of WEEE.

Keywords: Waste electrical and electronic equipment (WEEE); Electrical home appliances (EHAs); Recycling; Extended producer responsibility (EPR); Printed circuit boards (PCB); Valuable metals; Recovery

Contents

1. Introduction

The advent of electrical and electronic equipment (EEE) with new functions and design time to time, stimulate consumers' purchasing desire towards the latest equipments. This leads the rapid increase in the sales of new facilitated models of EEE in the world (LaCoursiere, 2005). Due to the rapid replacement of old model by latest advanced model time to time causes short average lifespan of EEE and consequently leads to yield mass generation of waste electrical and electronic equipment (WEEE). The generation of tremendous amount of bulky WEEE containing variety of hazardous substances is a major social problem and threat to the environment (Brodersen et al., 1992; Lee, 2005).

For example, several million tonnes of WEEE are being generated in the U.S., EU and Japan (Kang and Schoenung, 2005; Beck, 2004; Clean Japan Center, 2002). In 2001, the quantity of electronic wastes generated in the U.S. was estimated around 2.26 million tonnes and these were mainly: (1) video products such as TVs, VCR decks, camcorders and TV/VCR combinations, (2) audio products including compact disk players, rack audio system and compact audio system, and (3) information products like PC, computer monitors, telephones and fax machines. Accordingly, a tremendous amount of electrical wastes, viz. electrical home appliances (EHAs) such as refrigerators, washing machines and air conditioners is generated every year.

In the case of EU, total electronic waste generation was found 5 million tonnes, simultaneously the average quantity of the generation of electronic wastes was observed 14 kg per person in the year 2004 (Beck, 2004). Despite of an enormous amount of WEEE is being generated every year in the U.S. and EU, their treatments are simply relying on incineration or landfill. In the EU, when the WEEE directives are successfully enforced, they can make much contribution towards the constitution of resources-recirculation society that will satisfy both the protection of environment and the conservation of resources (Europa, 2006; Fauve-Buresi, 2006).

In addition, as Korea enjoys distinguished economic growth since last two decades, its sale volume of EEE has increased steadily (KEA, 2006). The rapid growth of the IT industries particularly due to the pivotal role of semiconductors is the major driving force for the expansion of our domestic market. Due to the breakage of traditional joint large family to nuclear small family creates the need of more household materials causes the expansion in sale. As the number of end-of-life (EOL) EEE is inevitably increasing with the sale expansion, effective measures for treating EOL EEE are necessary. Particularly, the recycling of WEEE with industrial raw materials could be one of the utmost significance as Korea has scarcely natural resources and limited land area in comparison to its dense population.

In 1992, based on the waste control act, the waste deposit–refund system was introduced in Korea (Park, 2005; MOE, 2006). In this system, a deposit is imposed at a constant rate on products and packages that are readily recyclable, and is returned after the recycling of those. In respect to other WEEE, first of all TVs and washing machines were included in the system in 1992. The refrigerators and air conditioners were included in the years 1993 and 1997, respectively. The extended producer responsibility (EPR) system was enforced to promote recycling practices in 2003. The EPR system holds producers accountable for the entire life cycle of their products in order to incite innovation in product design, materials use and business management through economic incentives. TVs, refrigerators, washing machines, air conditioners and PCs were selected as primary targets (Park, 2005; ENVICO, 2006). Audio equipment and mobile phones were included under EPR system in 2005 and facsimiles and, printers were added in 2006. The recycling rate of WEEE in compliance with the introduction of the EPR system is still not satisfactory, compared to the rapid generation of WEEE due to EEE's short end-of-life. This may be attributed to insufficient infrastructure for collecting WEEE, and lack of consumers' understanding about the system as well as feasible technologies for the recycling of WEEE.

This paper describes the present status of generation and recycling of waste electrical and electronic equipment, namely TVs, refrigerators, washing machines, air conditioners, personal computers (PC) and mobile phones in Korea. The plant technologies adopted by three recycling centre for the recycling of waste refrigerators and TVs are also explained. The commercial processes and the status of developing new technologies for the recycling of metallic values from waste printed circuit boards (PCBs) is also described briefly.

2. Generation and recycling of WEEE

2.1. Waste electrical home appliances

The sales of electrical home appliances such as TVs, refrigerators, washing machines and air conditioners continued to increase till 2000 and then are tending downwards. As shown in Table 1, the sales of EHAs increased from 5.6 million units in 1990 to 7.8 million units

Table 1
Sales volume of electric home appliances and estimated volume of their obsoletes and wastes (unit: thousand)

	Year				
	1990	1995	2000	2003	2004
Sale	5636	7609	7848	6574	5855
Obsolete	–	3662	5544	5765	6771
Waste	–	–	1257	1562	2016

in 2000, accounting for 40% growth. The following factors are expected for the increase in sale volume of EHAs: (1) simple population growth, (2) improvement in living standards, (3) increase in number of households and (4) decrease in product lifespan due to preference for new function and design. However, in the period 2000–2004 the sales decreased to 5.8 million units, i.e. around the 25% reduction. The reason for this decrease mainly attributed to the saturation of households with EHAs. The another reason for this decrease in sale observed is that the rapid increase in demand for specially designed small refrigerators to preserve traditional Korean pickle food "*kimchi*" made up of fermentated Chinese cabbage and radish plus red pepper, garlic, fruit and salted fish. Since the year 2000, the demand of very small refrigerator causes the rapid decline in the sale of normal big refrigerator in Korea. The sales volume of kimchi refrigerator was not included in the statistical data shown in Table 1 (KEA, 2006).

The estimated volume of obsolete electrical home appliances is calculated by predicting sales and average service life of EHAs (AEE, 2001; KNCPC, 2004a). The "obsolete" EHAs is defined as a potential waste that is generated due to the negligence of consumer towards the discard of defunct EHAs. The "waste" electrical home appliances are defined as obsolete EHAs that are actually discarded after use. The average service life of domestic EHAs is estimated around 10 years and accordingly the estimated volume of obsolete EHAs in 2000 is expected to be similar to the sale volume in 1990. In addition, the estimated volume of obsolete EHAs in 2004 is 6,771,000 units, which is approximately equal to the sales volume in 1995. The volume of waste electrical home appliances that is actually disposed of as end-of-life EHAs increases slightly every year and can be predicted on the basis of the statistics that were actually obtained in the past. As shown in Table 1, the volume of waste EHAs increases by 10% yearly, reaching only at a 20–30% level of the obsolete EHAs. Though the volume of EHAs has decreased since 2000, the volume of the end-of-life EHAs is expected to increase continuously in the next 4–5 years.

Fig. 1 shows the trend of estimated volume of waste EHAs during the years 2000–2005. During this period, the highest yearly increasing rates among the four waste items were obtained 19 and 14% for air conditioners and TVs, respectively. In case of TVs, the growing preference of customers towards large screen TVs, the advent of new products such as plasma display panel (PDP) and liquid crystal display (LCD) TVs might have caused the generation of waste EHAs (LaCoursiere, 2005). Particularly, consumers continue to replace existing analog TVs with digital one as Korea telecasted its first digital programs in 2001 and continuing to improve and expand the digital relay day by day (Digital TV, 2006). The items in the descending order of the waste EHAs volume are TVs, refrigerators, washing machines and air conditioners.

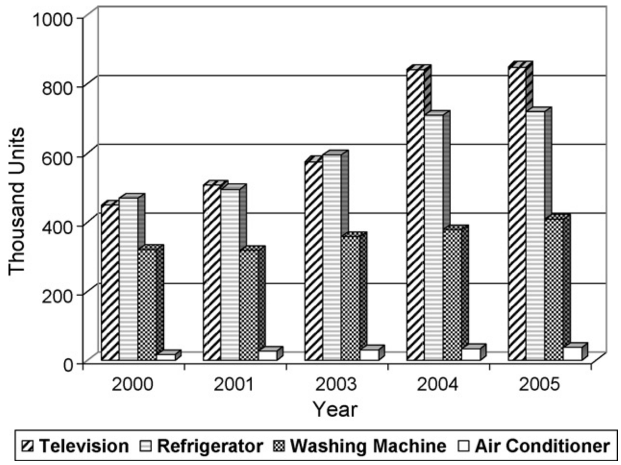

Fig. 1. Estimated volume of waste electric home appliances.

Waste EHAs are collected by local autonomous entities, distributors and recyclers and then treated by various means such as recycling, reuse, incineration, landfill, etc. (KNCPC, 2004a). The volumes of waste EHAs collected and treated during the 5 years (1999–2003) are shown in Fig. 2. About 1.3 million waste EHAs units were collected in 2000 and 2.3 million in 2003, increasing by 75%. Fig. 2 shows the volume of waste EHAs collected in 2003 exceeds up to 50% in comparison to the estimated volume of waste EHAs as presented in Table 1. The reason is the influence of EPR system since January 2003 on collection and treatment of waste EHA. However, the total volume of the waste EHAs collected, incinerated, landfilled and recycled were found only 40% in comparison to obsolete EHAs (KNCPC, 2004a).

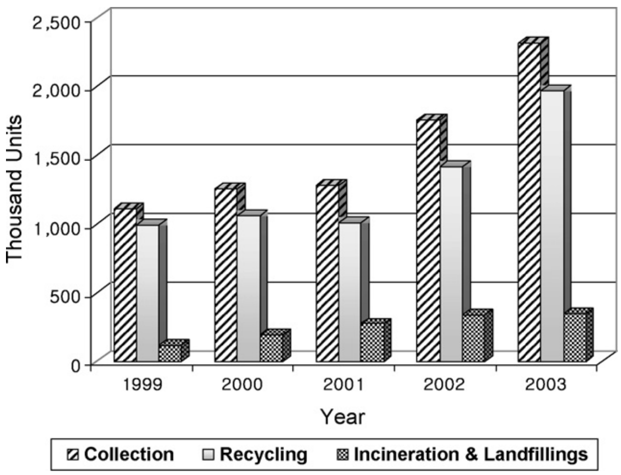

Fig. 2. Collection and treatment of waste electric home appliances.

The total annual amount of WEEE for mandatory recycling that were imposed on producers and importers under EPR system in 2003 was 41,881 tonnes equivalent of 854,000 units (KNCPC, 2004b). In terms of categorise by product, TVs was 273,000 units (8481 tonnes), refrigerators 298,000 units (19,100 tonnes), washing machines 274,000 units (13,700 tonnes) and air conditioners 9000 units (600 tonnes). The amount of mandatory recycling increased to 51,932 tonnes in 2004, gaining 25% over 2003. The total annual mandatory recycling amount of WEEE was calculated by the following equation up to the period 2004 (KNCPC, 2004a).

$$\text{Total amount of the annual mandatory recycling} = \frac{A+B}{2} + (C-A) \times 0.1 \times D \quad (1)$$

where A is the amount of waste EEE recycled in the year before last, B the amount of mandatory recycling in the previous year, C the amount of EEE shipped from the warehouse in the year before last and D is the recycling factor by the government.

Since 2005, the following equation has been applied in lieu of Eq. (1):

$$\begin{aligned}&\text{Total amount of the annual mandatory recycling}\\&\quad = \text{amount of EEE shipped from the warehouse shipment year}\\&\qquad \times \text{mandatory recycling rate}\end{aligned} \quad (2)$$

In the year 2006, the rate of mandatory recycling 13, 13, 23, 2 and 9% is fixed by Government of Korea for TVs, refrigerators, washing machines, air conditioners and PCs, respectively (ENVICO, 2006; KNCPC, 2004b). Moreover, for the mobile phones, audio equipments, copy machines and facsimiles the rate of mandatory recycling is fixed 15, 13, 8 and 8%, respectively (MOE, 2006).

Fig. 3 shows the volumes of waste EHAs recycled by producers during the years 1999–2004. Since 1998 after the establishment of recycling centers by electronics industry in Korea the treatment and recycling have been continuing for waste refrigerators, washing machines, air conditioners, etc. (AEE, 2006a; KNCPC, 2004a). Recycling centers are now being operated at three locations by three major electronic companies, handling a total amount of 880,000 units/year (capacity/year): (1) Asan Recycling Center (new name, Chung Bu Region Recycling Center; location, Asan-si, Chungcheongnam-do, Korea) by Samsung (267,000 units) (Asan Recycling Center, 2006), (2) Chilsu Recycling Center (new name, Yong Nam Region Recycling Center; location, Haman-gun, Gyeongsangnam-do, Korea) by LG (250,000 units) (Chilsu Recycling Center, 2006) and (3) Yongin Recycling Center (new name, Metropolitan Region Recycling Center; location, Yongin-si, Gyeonggi-do, Korea) by 3-major co. (363,000 units). Waste TVs are recycled on commission by several private recycling plants. During the period 2000–2003, the recycling of waste EHAs were increased up to 70%. The 625,000 and 1,051,000 units of waste EHAs were recycled in the years 2000 and 2003, respectively. This rapid increase in rate of recycling of waste EHA is expected due to the implementation of EPR system. The total amount of waste EHAs recycled in 2004 except for TVs was 844,000 units, reaching almost 96% of the capacity of three recycling plants (AEE, 2006a). However, all waste EHAs collected by producers are thought to be

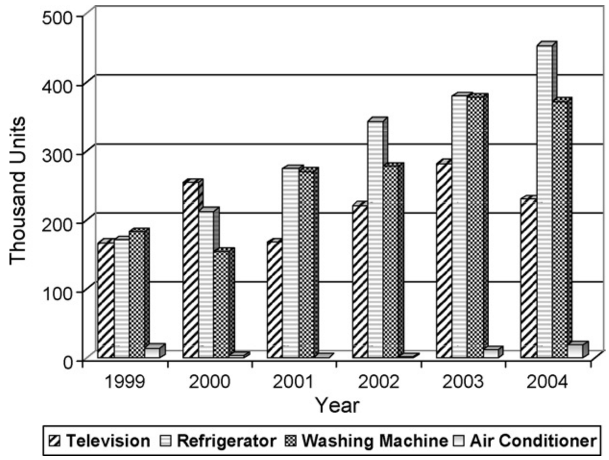

Fig. 3. Volume of waste electric home appliances recycled by producers.

recycled but comparative study of Figs. 2 and 3 shows only 53% of the collected waste EHAs has been recycled in Korea. The recycling amount of waste EHAs increases every year, however, in case of waste TVs the trend for recycling is fluctuating. The recycling of waste TVs is being practiced through the glass-to-glass recycling (AEE, 2006b; Narae Recycle Center Co., Ltd., 2006). The relocation of cathode ray tube (CRT) plant in abroad and subsequently the rapid reduction of glass demand for CRT causes the fluctuation in the quantity of the recycling of waste TVs. Accordingly, it is necessary to develop new effective technology for the applications of glass-to-lead recycling to accelerate the rate of recycling of waste TVs (Hainault et al., 2000).

2.2. *Waste PCs and mobile phones*

Due to much advancement in information technology (IT) in Korea, a huge number of PC sets and mobile phones are being used and comparatively, the disposal, collection and recycling of these electronic wastes are insignificant. Fig. 4 shows the yearly estimated volumes of sales, obsolete and waste of PCs (KIGAM, 2003; Park, 2005). As shown in Fig. 4, the sales volume has reached to a peak of 3,000,000 units in the year 2000 and then tended to downwards in successive years. Korea has approached the society full of information technology, therefore the cumulative sales volume of PCs reached over 10,000,000 units in 1997. On the basis of the assumption that 4–5 years average lifespan of the PCs, the volume of the obsolete PCs was estimated at about 1 million in 2000 and 1.6 million units in 2002 (AEE, 2002). Obviously, the increase in volume of obsolete in successive years could be expected due to the 5 years short average lifespan of PCs.

Since Korean households seem to regard PCs as assets and it may take up relatively a small space compared to EHA, they generally tend to keep obsolete TVs at home. Therefore, the volume of obsolete PCs has passed over 1.0 million units since 2000, but the volume of waste PCs generated found only 30% in comparison to the obsolete PCs (KIGAM,

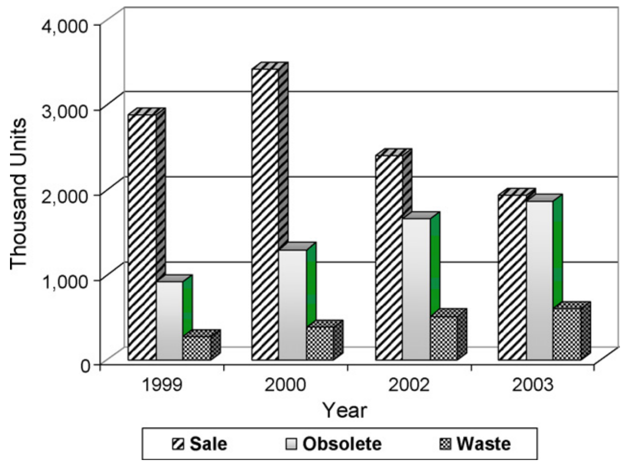

Fig. 4. Estimated volume of obsolete and waste personal computers (PCs).

2003). However, the rapid discharge of obsolete PCs by households could be expected for that moment when the high-performance PCs will be spread throughout Korea. Since the recycling of waste PCs is still not in proper/organised manner in Korea, its statistical data is not available. According to the Korean Association of Electronics Environment (AEE), the number of the waste PC recycled by producers in 2002 was 33,000 units, accounting for mere 6% of the estimated waste PCs. After the implementation of EPR system in subsequent year, the volume increased to 256,000, accounting for almost 50% of the estimated waste PCs (Park, 2005).

The mobile phones market is one of the leading areas for Korea in world. Fig. 5 shows that in the year 2002 total population of mobile phone subscribers was more than 30 million,

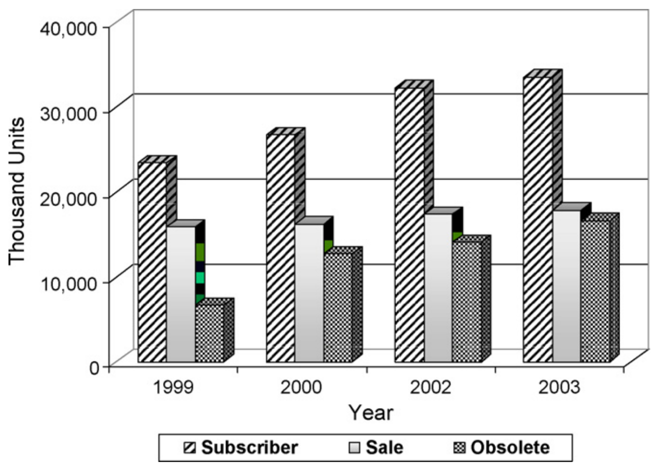

Fig. 5. Estimated volume of obsolete mobile phones.

i.e. 75% of total the population (KNCPC, 2004a; Song, 2004). The sales volume of mobile phones per year is almost constant, i.e. 15 million every year. The estimated volume of obsolete mobile phones was 6.6 million units in 1999 and doubled the next year. For the years 2000–2002, the estimated volume of obsolete mobile phones accounts for about 80% of the sales volume, indicating a frequent replacement. This is due to the short lifespan of mobile phones as continuous changes in mobile phones features and capabilities by competent Korean mobile phones producers. However, the volume of waste mobile phones collected and recycled was small. In the year 2003, about 4 million units of waste mobile phones were collected by Korean telecommunication industries. The waste mobile phones collected are either exported (2 MM units) or treated as follows: (1) incineration/landfill (1.8 MM), (2) reuse (0.1 MM) and (3) recycling (0.1 MM) (Song, 2004; Lee, 2006). Due to the small size of mobile phones, it makes less attention to discard as waste and generally remains inside the house as obsolete.

3. Recycling technologies of WEEE

3.1. Waste electronic home appliances

As mentioned earlier, the recycling of waste electronic home appliances has been performed successfully, due to the implementation of EPR system in 2003. Three items such as refrigerators, washing machines and air conditioners are being recycled at the recycling centers established by domestic electronic companies and TVs are being commissioned to private CRT recyclers for the glass-to-glass recycling. The processing technologies practiced at three different recycling centers differ slightly, but generally consist of the following mechanical treatment steps: (1) pretreatment process for dismantling main parts, (2) shredding/grinding processes for size reduction and liberation of components and (3) beneficiation process for the separation and recovery of component materials (AEE, 2006a; Samsung Global Environment Research Center, 2006; KNCPC, 2004a).

A flow diagram of waste refrigerators recycling plant at the Yongin recycling center is shown in Fig. 6 (Yongin Recycling Center, 2006). The recycling process of waste refrigerators consists of four stages: (1) sorting and dismantling by hand, (2) shredding of main body, (3) separation and recovery of urethane and (4) separation and recovery of metals and non-metallic components. The waste refrigerators are collected and transported to the recycling center. After the arrival of waste EHA in recycling center, first of all the waste refrigerators are sorted and then subjected to the dismantling process.

In the dismantling step, compressors and transformers which have difficulties to crush and some easily detachable parts are removed from main body by hand. Refrigerant (CFC R12) as well as oil are removed from the compressors and are stored. Refrigent is stored after the liquefaction. After dismantling of the refrigerator, main bodies of waste refrigerators are sent for two-stage shredding process. The main bodies are reduced to >70 mm in the first stage and then to >30 mm in the second stage. The shredding process of the Asan Recycling Center consists of three shredding stages: 45 mm → 25 mm → 19 mm. Polyurethane is the main particulates generated in the course of shredding and collected in bag filters.

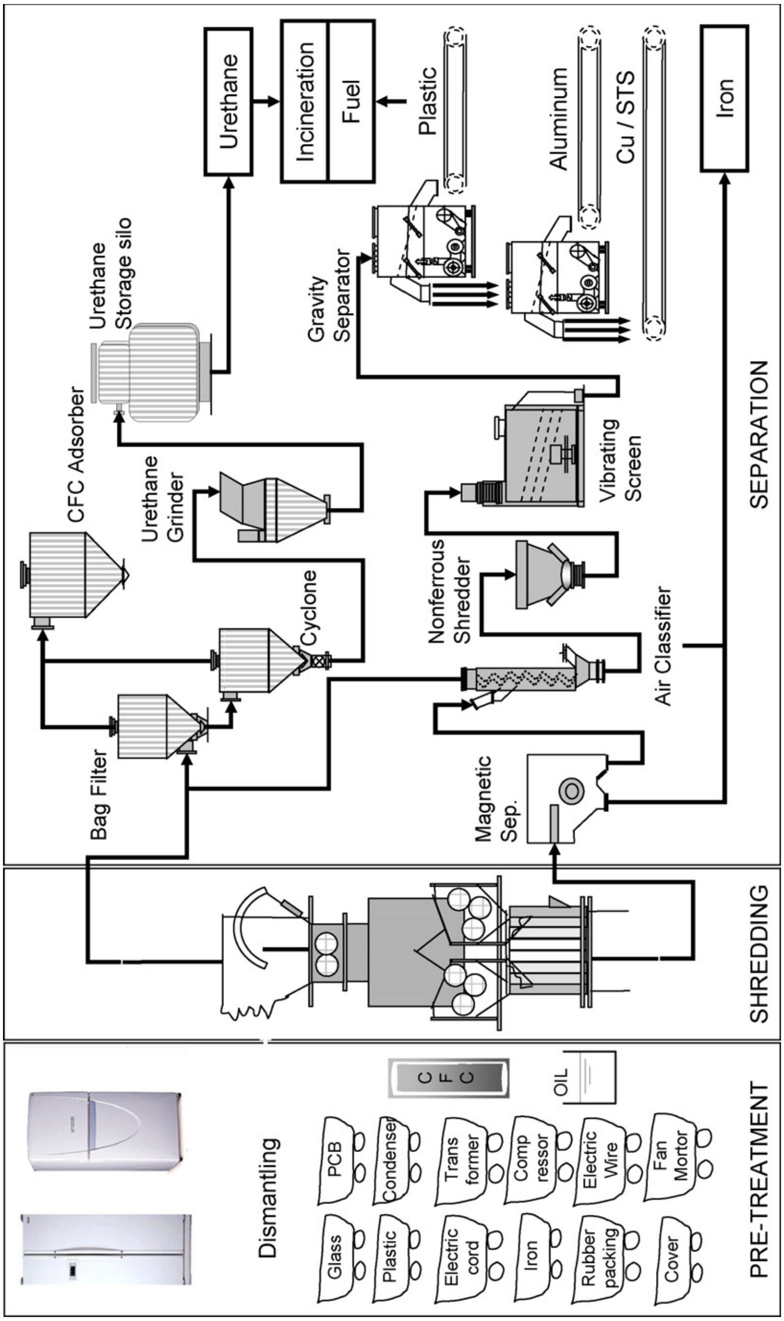

Fig. 6. Simplified flow diagram of waste refrigerators recycling plant.

The shredded products are subjected to magnetic separation process for the separation of the magnetic and non-magnetic components. The magnetic materials containing iron as a main component are recovered in magnetic separation process. The non-magnetic components are passed through the air classifier that separates light polyurethane and heavy non-ferrous metals components. The polyurethane is collected in bag filter. The non-ferrous metals are put into a shredding process, crushed into 5–8 mm sizes, and liberated into individual substances. The shredded products are classified into 3–5, 5–8 and >8 mm sizes by putting it into vibratory screen. Then plastics, aluminum and copper particles are separated from the shredded products by gravity separation. The back-filtered polyurethane particles are separated using cyclone, then grounded into powder and stored in silo. The CFC gas originally mixed with the polyurethane particles are back-filtered, separated using cyclone, adsorbed in CFC adsorber and stored. The polyurethane and plastics are incinerated or shipped to cement plants for the utilisation as energy source. All components dismantled and recovered are sold to private recyclers, but printed circuit boards containing small content of valuable metals remain untreated because they have little metallic values and economical recovery processes have not been yet developed. Reclaimed urethane and plastics are also incinerated, so their recycling schemes have to be sought out.

Fig. 7 shows a schematic diagram for recycling waste TVs and CRT monitors at the Narae Recycling Center (Narae Recycle Center Co., Ltd., 2006). The process consists of recycling mainly CRTs and other components. Considering the weight of a CRT (Braun tube) accounts for about 50% of a TV, recycling it effectively is of great importance to the success of overall recycling (Oberle, 2004; Kang and Schoenung, 2005). In a recy-

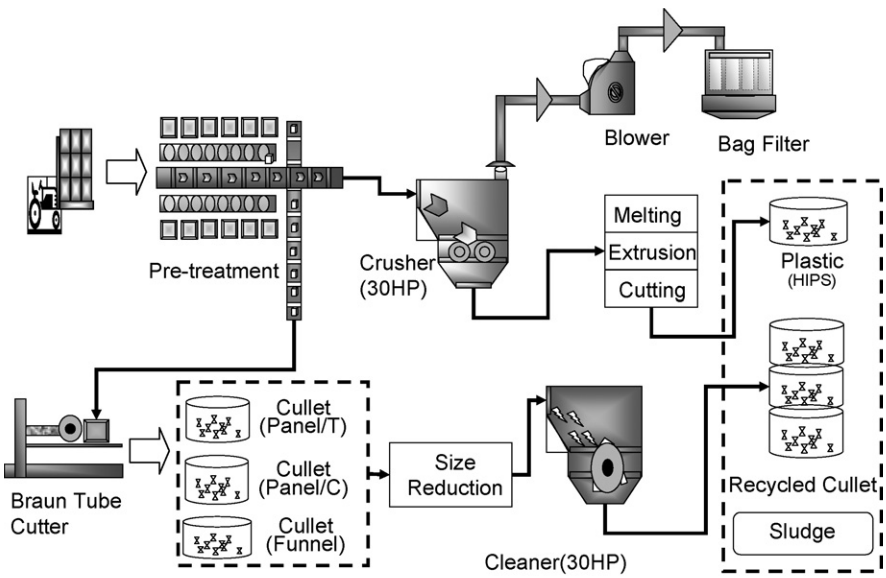

Fig. 7. Simplified flow diagram of waste televisions and CRT monitors recycling plant.

cling plant, collected TVs are first put into the pretreatment step and then dismantled into CRTs, PCBs, plastics, wood cases and scrap iron by hand. The plastics are composed mostly of high-impact polystyrene (HIP) and some of acrylonitrile butadiene styrene (ABS). These plastics are put on the market after being crushed, melted, extracted and shredded.

CRTs are classified as industrial and civilian uses and color CRTs classified into color picture tube (CPT) and color display tube (CDT). Their recycling processes consist of a series of cutting, shredding, shadow mask removal, crushing, and washing and cullet recovery. As the funnel glass contains lead component, the panel glass should be separated from the funnel glass for the recycling as a raw material for new CRTs. A variety of cutting technologies to separate the panel from the funnel are available (Bock, 2006). In general, fritted joint portion of a CRT are cut with a heating wire, diamond saw, laser, etc. Narae Recycling Center is operating the process to separate the panel and the funnel using a diamond saw. Youngchang separates the panel and the funnel by hand, but a heavy loss of panel glass is occurred due to the lack of precise cutting.

There are several methods to remove the coated layer of the surface of panels and funnels: suction washing, high-pressure washing, glass blasting, drum washing, and acid and alkaline washing. As shown in Fig. 7, a drum washing method is employed at Narae. In this method, by the friction between cullets from separate panels or funnels charged with water in a rotating drum, coating on the cullet surface can wear down and finally be removed. At Youngchang, an inclined drum attached with a spiral screw is employed to improve the friction efficiency between cullets. The method definitely improves productivity, but has a disadvantage of generating glass sludge as a secondary waste that has limited applications. Yet there is a study on the recovery of yttrium fluorescent material from panel sludge (Jeon et al., 2001). Presently Narae is considering the change of drum washing to suction washing. Youngchang used to remove the fluorescent film from panel cullets with nitric and hydrofluoric acids, but switched to drum washing due to environmental issues (Lee et al., 1998a; Jeon et al., 2001). As explained earlier, the rate of glass-to-glass recycling of CRTs is discouraging since CRT producers pulled out their manufacturing equipment from Korea. Therefore, Narae is developing technologies to use CRT cullets as bricks, aggregate, glass titles, rubbing compounds for blue jeans and smelting flux.

3.2. Waste PCs and mobile phones

Recyclers are much interested in recycling PCBs built in PCs and mobile phones since they contain valuable metals including the precious metals such as gold, silver, palladium and rhodium (Hoffman, 1992; Bernardes et al., 1997; Lee et al., 1998b). As shown in Fig. 4, there are keen competitions among recyclers in securing valuable waste PCs because the volume of waste PCs discharged is only 30% of obsolete PCs. The recycling of waste PCs for recovering valuable metals, including precious metals is at an insignificant stage since collected waste PCs are exported to developing countries and PCBs in waste PCs are often sold as second hands (Lee, 2003).

Waste PCs are separated into three parts, namely body, keyboard and monitor. The most of the monitors are shipped to TVs recycling facilities. The body is disassembled mainly

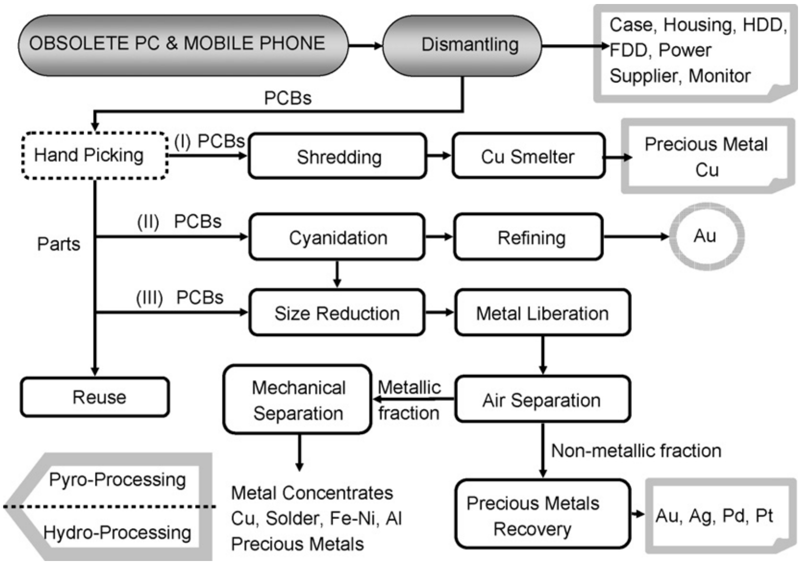

Fig. 8. Strategic processes for the recycling of waste PCBs.

into housing, system board (motherboard), hard disk drive, floppy disk drive and power supplier. The keyboard is dismantled into case and board. The main components of the body and keyboard are plastics, iron, aluminum, printed circuit boards, etc. The plastics from the body and keyboard are sorted into polystyrene (PS) and acrylonitrile butadiene styrene. Then it is putted into a series of crushing, melting, extrusion and cutting as shown in Fig. 7. The PB and ABS pellets are sold as raw materials and iron and aluminum as scraps.

The key to the success of recycling waste PCs and mobile phones hinges on economical and efficient technologies for recovering valuable metals from PCBs. Recycling technologies to recover valuable metals from PCBs are generally classified into the following methods: (1) pyrometallurgical process typically practiced at copper smelters (process I in Fig. 8) and (2) combined process of mechanical pretreatment and hydrometallurgical processes (process III). Process I is being applied recently in Korea. PCBs shredded to about 5 mm size are putted into either copper or QSL lead smelter for the recovery of copper and precious metals (Lee, 2002). The pyrometallurgical approach has notable disadvantages of requiring a long-term recovery, air pollution, a loss of noble metals and heavy transportation costs particularly in Korea, and failing the recovery of aluminum, zinc, tin and lead (Sun, 1991). Accordingly, in recent years Korea has made every effort to develop process III as environmentally friendly recycling technology, involving mechanical pretreatment in combination with hydrometallurgy (Lee and Kim, 2004).

In initial stage of recycling PCBs, there were a number of recyclers that employed the cyanidation process (process II) for the recovery of gold on edge connectors, IC chips, CPU and copper pins mounted to PCBs, but they have almost stopped operation due to high labour cost and environmental issues. Process III involves efficient liberation and separation processes of metallic components from non-metallic components, followed by hydrometallurgical route. The mechanical pretreatment is usually required to employ the hydrometallurgical route for the recycling of valuable metals from PCBs (Cui and Forssberg, 2003). Direct leaching of metallic fractions coated or encapsulated with plastics and ceramic rarely accomplishes effective extraction of valuable metals from PCBs. Thus, metallic components have to be liberated from non-metallic components such as plastics and ceramic to readily contact with leachant. In addition, the effective separation of metallic components in mechanical pretreatment makes the extraction and purification processes of metals easier. Lee et al. (1997) and Jeong et al. (2006) have reported that the metal liberation of 95–100% could be achieved from PCBs utilizing a swing hammer type impact mill or stamp mill, but those pretreatment processes were not applied in the commercial plant yet. As the characteristics of metal liberation from PCBs are closely related to the grinding equipment, the technology development for metal liberation should be associated with development of the grinding equipments. Korea is encountering difficulties to develop the technology for metal liberation from PCBs due to the lack of the fundamental technology for the manufacturing of grinding equipments.

The liberated metallic and non-metallic particles are efficiently separated by air separation method. Since the precious metals present in PCBs exist as thin layer on the surface of copper, nickel and iron or bonding wires, they are concentrated as fine particles in the non-metallic components during the grinding process for metal liberation. The precious metals concentrated in the non-metallic components are leached with aqua regia and then recovered by the conventional method. The residues are incinerated or shipped to a copper smelter for further processing. The metallic components iron, nickel, copper and aluminum are separated by magnetic, eddy current and electrostatic separation techniques. The more efficient separation process is required to obtain the higher grade of recovered metal component, but the degree of metal liberation should be higher preferentially.

A series of hydrometallurgical processes, including leaching, separation and recovery have been employed for the recovery of valuable metals from the metallic concentrate. Eco-friendly and energy-saving processes are necessary to comply with stringent environmental regulations. Some Korean technologies are under investigation for leaching of the valuable metals from waste PCBs, viz. electro-generated chlorine leaching (Kim et al., 2005, 2006), ammoniacal leaching (Koyama et al., 2003, 2006) and bacterial leaching (Ahn et al., 2005a,b). The development of individual process or combined processes, including precipitation, cementation, solvent extraction, ion exchange and supported liquid membrane is underway (KIGAM, 2006).

The recycling of waste mobile phones is very attractive since their volume is small and PCBs containing relatively high contents of precious metals such as gold, silver, palladium, etc. Fig. 9 shows two methods of recycling processes developed in Korea. The first method (process I) is identical to process I shown in Fig. 8, involving shredding of waste PCBs and shipment to a copper smelter. The second method (process II) is comprised of shredding, incineration, melting into copper alloy containing precious metals and their refining processes utilizing hydrometallurgical route. However, the recycling plant operation in Korea does not go on smoothly because most of the waste mobile phones collected are exported or incinerated and landfilled, and only 2.5% of waste mobile phones collected are recycled.

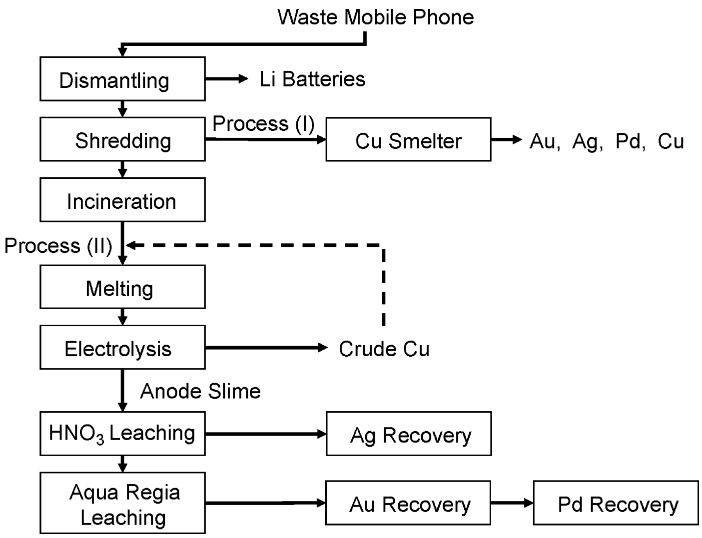

Fig. 9. Flow sheet for the recycling of metal values from waste mobile phones.

A pilot plant to recover cobalt from spent lithium-ion batteries of waste mobile phones is under operation because it contains valuable cobalt.

4. Conclusions

The EPR system has been enforced in Korea since 2003. As the enormous amount of WEEE are being generated every year, the mandatory recycling amount of WEEE keeps rising and the target items subject to mandatory recycling increases at same time. The target rate of recycling of items is also increasing. In the case of waste TVs and PCs, the target rate was 55% by weight in 2005 and increased to 65% in 2006 (ENVICO, 2006). The recycling rate for mobile phones, audio, refrigerators increased from 60 to 70% and for washing machines and air conditioners it found increased from 70 to 80% during the same period.

The Korean government is making consistent efforts to improve the recycling rate to the standards indicated in the EU directives for WEEE. The acquisition of sound recycling technologies is firmly believed to precede the execution of any policies on WEEE recycling. Unfortunately, Korea has not held satisfactory recycling technology coping with the EU standards. For example, since all CRT plants have been relocated in abroad and subsequently the demand for glass for the manufacturing of CRT is rapidly reduced as explained earlier, the recycling of waste TVs is not performed smoothly. The low-valued waste PCBs containing a variety of hazardous heavy metals are not recycled and instead incinerated and landfilled, it makes the matter worse. In addition, all minor components and wires collected in the dismantling stage of recycling operations are not effectively reclaimed.

In recent years, the crisis of energy and mineral resources resulting from their depletion arouses keen interest in waste recycling. WEEE contains valuables such as precious metals, iron, stainless steel, non-ferrous metals, plastics, glass, etc. In order that resource-deficient country Korea may survive as an industrial country, it should make sustained efforts to develop the technologies to recycle WEEE as secondary resources for recovering metal values as well as to secure raw materials. Korea also has to explore every recycling avenue to recover energy from WEEE or make it secondary raw materials for the advanced industries.

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References

Ahn J-W, Kim M-W, Jeong J-k, Lee J-c, Kim D-G, Ahn J-G. Biological leaching of Cu, Al, Zn, Ni, Co, Sn and Pb from waste electronic scrap using thiobacillus ferrooxidans. J Korean Inst Resour Recycl 2005a;14(1):17–25 [in Korean].

Ahn J-W, Jeong J-k, Lee J-c, Kim D-G. Bioleaching of valuable metals from electronic scrap using fungi (*Aspergillus niger*) as a microorganism. J Korean Inst Resour Recycl 2005b;14(5):24–31 [in Korean].

Asan Recycling Center. Mailing address: Yeomjak-ri, Dunpo-myeon, Asan-si, Chungcheongnam-do, Korea. Contact: +82-41-531-8811; 2006.

Association of Electronics Environment (AEE). Current status of collection and recycling of waste electronics. AEE Final Report. Seoul, Korea; December 2001 [in Korean].

Association of Electronics Environment (AEE). A study on the collection and recycling of obsolete PC and policy for its improvement. AEE Report. Seoul, Korea; November 2002 [in Korean].

Association of Electronics Environment (AEE). http://www.aee.or.kr/recycle/recycle_004.asp; 2006a [in Korean].

Association of Electronics Environment (AEE). Leading company of *e*-Recycling, Sambu Co. *e*-Recycling 2006b;18:26–7 [in Korean].

Beck M. A feast for bureaucrats, protectionists and environmental fundamentalists. Recycl Int 2004(March (2)):16–21.

Bernardes A, Bohlinger I, Rodriguez D. Recycling of printed circuit boards by melting with oxidizing/reducing top blowing process. In: Mishra B, editor. Proceedings of sessions and symposia sponsored by the extraction and processing division. TMS; 1997. p. 363–75.

Bock A. CRT recycling in closed loop. In: Proceedings of 5th international electronics recycling congress. Birrwil: ICM AG; 2006.

Brodersen K, Tartler D, Bergmann HW, Werner GD, Eder S. Scrap of electronics; hazardous waste or raw material resource? In: the ASM European Office, editor. Proceedings of the 1992 conference on the recycling of metals, the European Council of ASM International and its Technical Committee. Belgium: ASM; 1992. p. 45–51.

Chilsu Recycling Center. Mailing address: Chilseo-myeon, Haman-gun, Gyeongsangnam-do, Korea. Contact: +82-55-586-0420; 2006.

Clean Japan Center. Tokyo, Japan: Recycling-Oriented Society; March 2002.

Cui J, Forssberg E. Mechanical recycling of waste electric and electronic equipment: a review. J Hazard Mater 2003;B99:243–63.

Digital TV. http://www.digital-tv.or.kr; 2006 [in Korean].

ENVICO (Korea Environment and Resources Corporation). http://www.envico.or.kr/language/Eng/epr/extended/Eng_Extended_Outline_View.htm; 2006.

Europa, Environment-Waste Electric and Electronic Equipment. http://europa.eu.int/comm/environment/waste/weee_index.htm; 2006.

Fauve-Buresi H. WEEE/RoHS: a challenge for industry. In: Proceedings of 5th international electronics recycling congress; 2006.

Hainault T, Smith DS, Cauchi DJ, Thompson DA, Fisher MM, Hetzel C. Minnesota's multi-stakeholder approach to managing electronic products at end-of-life. In: Proceedings of the 2000 IEEE international symposium on electronics and the environment. IEEE; 2000. p. 310–7.

Hoffman JE. Recovering precious metals from electronic scrap. JOM 1992;44(7):43–8.

Jeon J-M, Lee J-c, Jeong J, Kim N-C. Recovery of yttrium from the sludge generated in recycling process of the obsolete CRT. J Korean Inst Resour Recycl 2001;10(6):22–8 [in Korean].

Jeong J, Kim M-S, Yoo K, Lee J-c. Effect of physical pre-treatment on liberation of metal from waste printer PCBs. Appl Chem 2006;10(1):35–8 [in Korean].

Kang H-Y, Schoenung JM. Electronic waste recycling: a review of U.S. infrastructure and technology options. Resour Conserv Recycl 2005;45:368–400.

Kim M-S, Lee J-c, Jeong J, Kim B-S, Kim E-Y. Leaching of copper from waste printed circuit boards using electro-generated chlorine in hydrochloric acid. J Korean Inst Resour Recycl 2005;14(5):45–53 [in Korean].

Kim E-Y, Kim M-S, Lee J-c, Jeong J, Kim B-S. Leaching of copper from waste printed circuit boards using electro-generated chlorine in hydrochloric acid solution. In: Howard SM, et al., editors. EPD congress 2006. Proceedings of sessions and symposia sponsored by the extraction and processing division (EPD) of TMS. Warrendale: TMS; 2006. p. 929–33.

Korea Electronics Association (KEA). http://www.gokea.org/neweiak/eng/; 2006.

Korea Institute of Geoscience and Mineral Resources (KIGAM). Development of commercial technology for recovering precious metals, 21C Frontier R&D Program. Final Report C-A-1-1. Ministry of Science and Technology; 2003 [in Korean].

Korea Institute of Geoscience and Mineral Resources (KIGAM). Development of total recycling technology for waste electric and electronic equipment, 21C Frontier R&D Program. Final Report 2C-A-1-1. Ministry of Science and Technology; 2006 [in Korean].

Korea National Cleaner Production Center (KNCPC). The planning for the product's end-of-life management. KNCPN Report-2004-RE-4. Seoul, Korea: KITECH; 2004a [in Korean].

Korea National Cleaner Production Center (KNCPC). Sustainable Ind Dev 2004b;7(2):15–8 [in Korean].

Koyama K, Tanaka M, Lee J-c. Copper recovery from waste printed circuit board. In: Young CA, et al., editors. Hydrometallurgy 2003. Proceedings of the 5th international conference in honor of Professor Ian Ritchie, volume 2: electrometallurgy and environmental hydrometallurgy. TMS/SME/CIM; 2003. p. 1555–63.

Koyama K, Tanaka M, Lee J-c. Copper leaching behavior from waste printed circuit board in ammoniacal alkaline solution. Mater Trans 2006;47(7):1788–92.

LaCoursiere C. Electronic waste recovery business (E-128). Norwalk, CT, USA: Business Communication Company Inc. (BCC); 2005.

Lee J-c, Koyanaka S, Lee M, Ohya H, Endoh S. Recovery of copper, tin and lead from the spent printed circuit boards (PCBs) by the shape separation method. Shigen-to-Sozai 1997;113(5):357–62.

Lee J-c, Yang J-I, Chung H-S, Song B-S. Recycling of the obsolete PC. In: Workshop on the waste treatment and recycling. Daejeon, Korea: KIGAM; 1998a. p. 45–63 [in Korean].

Lee J-c, Jeong J, Yang J-I, Chung H-S. Technology for recovering valuable metals from printed circuit boards (PCBs) of the used personal computer. J Korean Inst Resour Recycl 1998b;7(3):58–66 [in Korean].

Lee J-c. Current status of recycling of precious metals from the industrial wastes. Trends Met Mater Eng 2002;19(2):25–32 [in Korean].

Lee HS. A study on the politics for supporting the improvement of recycling of industrial wastes by survey, analysis and estimation. Report E-B-1-1. Daejeon, Korea: Korea Environment Institute, Industrial Waste Recycling Research Center; June 2003. p. 552–608 [in Korean].

Lee J-c, Kim D-J. Development of technology for recovering valuable metals from industrial wastes in KIGAM. In: Product recovery and impurity control. I: pure products from clean processing. Proceedings of the 2004 Parker Center hydrometallurgy conference; 2004.

Lee KM. Eco-design and electronics waste recycling. In: International symposium on e-waste recycling coping with WEEE & RoHS. Daejeon, Korea: KIGAM; 2005.

Lee J-c. Private communication with SK networks, http://www.sknetworks.co.kr; 2006.

Ministry of Environment Republic of Korea (MOE). http://www.me.go.kr/; 2006 [in Korean].

Narae Recycle Center Co., Ltd. Mailing address: 1-1 Changgok-ri, Paltan-myeon, Hwaseong-si, Gyeonggi-do, Korea. Contact: +82-354-2863/4; 2006.

Oberle TG. Recycling of cathode ray picture tubes in a worldwide closed cycle. In: Proceedings of 3th international electronics recycling congress. Birrwil: ICM AG; 2004.

Park I-H. E-waste recycling policy in Korea. In: International symposium on e-waste recycling coping with WEEE & RoHS. Daejeon, Korea: KIGAM; 2005.

Samsung Global Environment Research Center. Green Samsung 2006;77:60–6, http://www.greensamsung.com [in Korean].

Song HT. Current status of the recycling of waste mobile phones and urgent problem. *e*-Recycling 2004;8:7–9 [in Korean].

Sun EYL. The recovery of metals from electronic scrap. JOM 1991;43(4):53–61.

Yongin Recycling Center. Mailing address: Doekseong-ri, Idong-myeon, Cheoin-gu, Yongin-si, Gyeonggi-do, Korea. Contact: +82-31-323-0475; 2006.

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Review

Management of used & end-of-life mobile phones in Korea: A review

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ABSTRACT

Environmentally sound management of end-of-life mobile phones is an issue of growing concern in Korea and around the world. This paper discusses the generation rate, collection systems, and recycling processes of used & end-of-life mobile phones in Korea. The results were based on review of the existing literature, a survey of 1090 consumers, site visits to electronic waste recycling facilities, and interviews with mobile telecommunication companies and environmental regulatory authorities. The results show that on average 14.5 million mobile phones have been retired annually in Korea over the period of analysis (2000–2007). A large fraction of used & end-of-life mobile phones has been stored at home waiting for disposal. Approximately five million used & end-of-life mobile phones have been collected by mobile telecommunication companies and producers annually between 2004 and 2007. The results of the consumer survey showed that the average Korean consumer typically replaces his/her mobile phone every 28.8 months. Since collection and recycling of mobile phones has only recently started, the methods and infrastructure for collection and recycling process for used & end-of-life mobile phones have not yet been well-established. More active collection activities and systems for used & end-of-life mobile phone are still needed, adding more collection points where consumers can drop off their used mobile phones. Producers, consumers, mobile telecommunication companies, and local governments should consider more collective actions that can be taken to promote successful collection and recycling schemes.

Contents

1. Introduction

One of the strongest demands for electronic devices by consumers is for mobile phones (also called cellular phones). This high demand is because they serve not only as an addition to traditional line telephones but also as a primary means of communication. In the world, the use of mobile phones has grown exponentially from the first few users in the 1970s to 4.6 billion in 2007 (ITU, 2009). The market for new mobile phones has been growing in many countries. More than 1.15 billion mobile phones were sold worldwide in 2007, a 16 percent increase from the 991 million mobile phones sold in 2006 (CNET News, 2008).

Korea's mobile phone services market began operating in 1984. The market has continued to grow and has now reached near saturation along with rapid developments in mobile phone technologies (Lee et al., 2009). Subscribers have increased from 20,353 in 1988 to more than 45 million in 2008, as shown in Fig. 1 (KCC, 2008). In 2008, more than 23 million mobile phones were sold in

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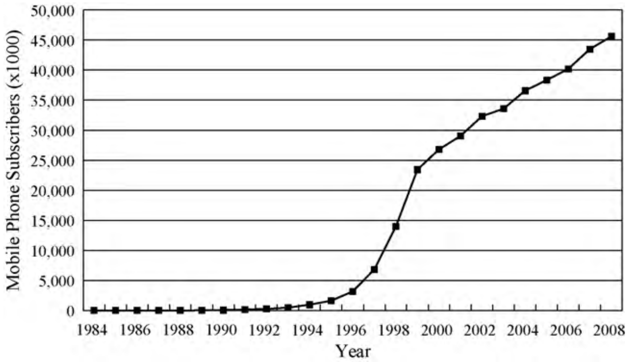

Fig. 1. The number of mobile phone subscribers in Korea.

Korea (KOSIS, 2008). Mobile phones are frequently replaced by new models having a more modern design and/or a larger number of functions. The large consumer demand for newer mobile products and the advanced development of ICT has resulted in a tremendous amount of obsolete mobile phones. The number of obsolete mobile phones worldwide is estimated to be higher than 500 million (Monteiro et al., 2007).

A mobile phone typically consists of many components (e.g., plastic housing, ferrous and non-ferrous metals, liquid crystal display, ceramics and glass, and printed circuit boards) commonly found in other electronic devices. It contains more than 30 elements, including precious metals (e.g., gold, cobalt, palladium, and rhodium) (UNEP, 2006). This device has rapidly progressed to smaller, lighter models weighing less than 100 g. The components in mobile phones vary from model to model, however. As the information technology advances, changes in the composition are expected.

A mobile phone along with its battery also contains toxic metals and organic chemicals (Table 1). The metals commonly found in mobile phones include arsenic, beryllium, cadmium, chromium, copper, lead, mercury, and nickel as well as organic constituents such as brominated flame retardants (BFRs), polycyclic aromatic hydrocarbons (PAHs), and poly vinyl chloride (UNEP, 2006). Lead is the most common metal typically found in the lead solder of printed circuit board. Cadmium can be found in batteries, plastic components as a stabilizer and an additive color pigment in some mobile phones. The type of batteries used for mobile phones has rapidly changed over the past decade as a result of the technical development of the battery. The types of batteries that are commonly found in mobile phones include lithium-ion battery using a lithium–cobalt compound or lithium–polymer, nickel–metal hydride battery using a nickel hydroxide compound, and nickel–cadmium battery (Takamoro et al., 2003). The nickel–cadmium battery, an older type of battery, has a lower energy density than the lithium-ion and nickel–metal hydroxide type of batteries; therefore, it is less commonly used in current mobile phones. This technical transition has significantly reduced the energy consumption as well as the potential environmental impacts due to the absence of lead and cadmium in the batteries. Despite this transition, nickel–cadmium batteries are still found in older mobile phones that are still in use or that have been discarded.

Table 1
Some chemicals and their sources in a mobile phone.

Compound	Component	Compound	Component
Cu	Circuit board, connectors	Br	Circuit board
Ni	Ni–Cd battery, Ni–Mn battery	Cd	Ni–Cd battery
KOH	Ni–Cd battery, Ni–Mn battery	Cr	Case, frame
Co	Li-ion battery	Pb	Circuit board
Li	Li-ion battery	LCD polymer	LCD screen
Al	Case, frame, battery	Mn	Circuit board
Fe	Case, frame, battery	Ag	Circuit board
Sn	Circuit board	Ta	Circuit board
		Ti	Case, frame
		W	Circuit board
		Zn	Circuit board

Adapted from UNEP (2006).

Toxic chemicals found in mobile phones such as arsenic, beryllium, cadmium, and lead are known to be persistent and bioaccumulative hazardous substances. During the recycling and uncontrolled treatment processes of the waste, some chemicals can be released into the environment and may pose a threat to human health. Some brominated flame retardants can form highly toxic dioxins and furans during incineration and recycling (Fishbein, 2002; Scharnhorst et al., 2005). Therefore, it is essential that unwanted mobile phones do not end up in landfills and incinerators. Because mobile phones are relatively small, impacts resulting from disposal may be overlooked as being minimal. However, the growth in their use has been so rapid that the impacts can become a significant concern. Thus, proper management of discarded mobile phones is an issue of growing concern in Korea and around the world (Most, 2003; Skerlos et al., 2003; BAN, 2004; Musson et al., 2006; UNEP, 2006; Lincoln et al., 2007; Monteiro et al., 2007; Long et al., 2008; Osibanjo and Nnorom, 2008).

A resource recovery and recycling program provides an alternative option to improper disposal of end-of-life mobile phones, batteries and their accessories. Even though there have been successful recycling practices for a number of solid waste streams (e.g., municipal solid waste, construction waste) over the last decade in Korea, the collection and recycling of used & end-of-life mobile phones has recently begun. The methods and infrastructure for collection and recycling processes for the phones have not yet been well-established. Recycling of these devices is an important concern, not only from the point of waste treatment, but also for the recovery of secondary materials such as plastic, copper, iron, aluminum, cobalt, and lithium. Especially, mobile phone waste recyclers are much interested in recycling printed circuit boards because the boards contain valuable metals. Thus, the key to the success of recycling mobile phones depend on economically efficient technologies for recovering secondary materials from printed circuit boards. Other recyclable components may include chargers, nickel–cadmium (Ni–Cd) batteries, lithium-ion batteries, small sealed lead-acid (SSLA) batteries, and nickel–metal hydride (Ni–MH) batteries. In recent years, limited studies have addressed collection and recycling efforts and potential problems associated with mobile phone waste management (Most, 2003; Jang et al., 2007; Monteiro et al., 2007; Long et al., 2008).

This paper presents an overview of the state-of-the-art knowledge on the collection and recycling of used & end-of-life mobile phones in Korea. In this study, the amount of retired and collected mobile phones, existing collection and recycling systems, and material recovery processes at mobile phone recycling facilities in Korea are discussed. It also reviews recent legislative efforts on collection and recycling of used & end-of-life mobile phones with an emphasis on the extended producer responsibility (EPR) policy. Finally, suggestions are made and current challenges are acknowledged concerning better recycling and management of used & end-of-life mobile phones.

2. Methodology

The methodology of this study included gathering data associated with annual domestic demands of mobile phones, questionnaire surveys, site visits, interviews and conversations, and review of available literature. The annual domestic demand and sales data of mobile phones were collected from the Korean Bureau of Statistics (KBS) and three major mobile telecommunication companies in Korea. The statistical data regarding the amount of used & end-of-life mobile phones retired and generated were obtained based on the consumer demands for electronics by the KBS, survey letters, previous research reports, and scientific papers (Choi and Kim, 2005; Park and Kim, 2005; Jang et al., 2007; KCC, 2008; Korea AEE, 2009).

A questionnaire survey administered to a total of 1090 consumers throughout the country was conducted to estimate the amount of used & end-of-life mobile phones that had been retired, stored, collected, and discarded. The detailed definition of the terms “retired” and “generated” can be found in the following section. The questionnaire was made of six major parts: background information of the household, lifespan of mobile phones, the number and model of used mobile phones stored at home, awareness of the importance of mobile phone waste recycling, economic values of used mobile phones by consumers, and options to deal with used mobile phones. The accuracy of representation of the sampling was examined by the basic information and the current possession status of the mobile phone obtained from the statistical data.

A number of visits to the major mobile telecommunication companies, about 20 mobile phone retail stores, two mobile phones recycling facilities, and the Korea Association of Electronics & Environment (Korea AEE) were made to support and supplement the information and the data gathered in the survey. The Korea AEE, a producer responsibility organization (PRO) for the electronics industry, has more than a decade of experience in managing electrical and electronic waste in Korea. Recycling processes for mobile phones waste were examined during the facility visits. Interviews and conversations with environmental authorities, electronic waste recycling industry experts, and the mobile telecommunication companies were conducted to obtain details with regard to recent progress and development associated with used & end-of-life mobile phone management. An expert survey was given to the mobile telecommunication companies, mobile waste recycling facilities, and refurbishers and exporters of used mobile phones to determine the material flow and current management and recycling issues. The material flow of used & end-of-life mobile phones was reconfirmed by on-site visits and interviews. Current literature was also reviewed to determine the management of used & end-of-life mobile phone in other countries.

3. Generation of used & end-of-life mobile phones in Korea

In order to develop proper management strategy for used & end-of-life mobile phones, it is important to characterize the quantity and composition of current mobile phone waste streams. Several methods can be used to estimate the number of used & end-of-life mobile phones to be retired. In this paper, the word “retired” refers to phones that have been taken out of mobile phone service. A large fraction of these products that has been retired is stored in households and destined to enter the waste stream at a later date. When used & end-of-life mobile phones are collected, reused and loaned, or lost and disposed of, these phones are referred to as “generated”.

The first simple and theoretical calculation is based on mobile phone subscribers and the assumed average lifespan of mobile phones (from 1 to 5 years). This approach is similar to one conducted for electronic waste by other researchers (Liu et al., 2006). It is assumed that the annual number of mobile phones retired is the increased number of mobile phone subscribers subtracted the first-time mobile phone subscribers for the same year. This calculation is based on the assumption that the Korean mobile phone markets are saturated and as each new mobile phone is purchased, an old one reaches its end-of-life. The calculated number of mobile phones retired per year is shown in Fig. 2. The lifespan of a mobile phone is inversely proportional to the number of retired mobile phones (i.e., shorter lifespan of mobile phone use results in more mobile phone waste). For example, it can be calculated that more than 17 million of mobile phone units with a 30-month lifespan were retired in 2008. It should be recognized that statistical data concerning the amount of sales and possession of mobile phones in Korea are available, but it is often difficult to precisely predict the annual amount of mobile phones retired using this approach because of the lack of statistic data on consumers’ consumption patterns (e.g., lifespan and the accumulated obsolescence ratio over a period of time).

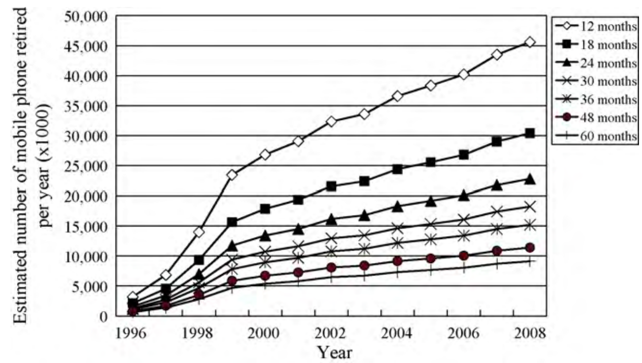

Fig. 2. The number of used & end-of-life mobile phones retired per year in Korea by using average lifespan.

The number of used & end-of-life mobile phones retired can be estimated by using annual domestic demand and number of subscribers of mobile phones. Table 2 presents the number of used & end-of-life mobile phones that have been retired during the period between 2000 and 2007. It was estimated that on average, approximately 14.5 million mobile phones each year were retired during the period. The average lifespan (or replacement period) of a mobile phone can be calculated by mobile phone subscribers divided by the amount of mobile phones retired. We determined that the lifespan of the device ranged from 2.0 to 2.8 year with an average of 2.4 year (or 28 months) in Korea. Other studies showed that in developed countries, on average, mobile phones are used for 18 months and are more frequently replaced by a newer model with a more modern design and/or newer technical features (Fishbein, 2002; Monteiro et al., 2007). In Nigeria, an average lifespan of a mobile phone was estimated to be 4 years (Osibanjo et al., 2008). This difference can be attributed to different economic conditions, cultural behavior, or market strategy for sales. When this approach is applied to unsaturated market conditions of mobile phones (e.g., developing markets for products with longer lifespan), care should be taken to recognize that the amount of used & end-of-life mobile phones retired can be overestimated.

More precise calculations of the number of “generated” mobile phones can be done by using the results of this study’s survey regarding the consumption patterns of consumers for mobile phone and the disposal options for these devices. Based on the results of the consumer survey, the percentage of used & end-of-life mobile phones returned to local retailers was almost 42.2%, while approximately 40.3% of the phones were stored at households for a perceived economic value. The percentage of mobile phones that were resold or loaned to others was about 11.6%, and the remaining percentage (5.9%) was lost or discarded. The survey results showed that on average, mobile phone users replace their phones with new ones approximately every 28.8 months, which was close to the average lifespan (i.e., 2.4 years), as shown in Table 2. It was also found that younger people replace their mobile phones more frequently than older people, as shown in Fig. 3. According to the

Table 2
Estimated number of used & end-of-life mobile phones retired per year in Korea by using domestic consumer demands (unit: 1000 units).

Year	Domestic demand for mobile phone[a]	New mobile phone subscribers[b]	Amounts of mobile phone retired	Replacement period (year)
2000	16,223	3374	12,849	2.1
2001	15,350	2229	13,121	2.2
2002	17,431	3297	14,134	2.3
2003	17,868	1249	16,619	2.0
2004	18,412	2994	15,417	2.4
2005	15,506	1756	13,749	2.8
2006	16,345	1859	14,487	2.8
2007	19,290	3297	15,993	2.7
Average	17,053	2507	14,546	2.4

[a] *Source*: KOSIS (2008).
[b] *Source*: KCC (2008).

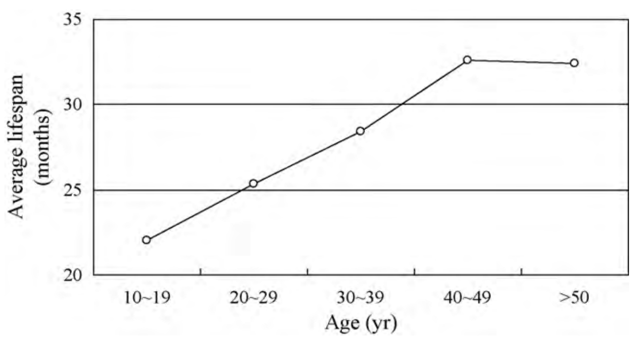

Fig. 3. Average lifespan of mobile phone by different age group.

results of the consumer survey, our estimates indicate that as of 2006, approximately 28 million used & end-of-life mobile phones were being stored at home and awaiting disposal (Jang et al., 2007).

Based on the consumer survey results along with the estimated number of used & end-of-life mobile phones retired per year (Table 2), household storage and generation rates (reuse, collection, and disposal) of the phones have been estimated, as shown in Table 3. The estimated numbers of household storage, reuse, collection, and others (lost/disposal) in Table 3 were calculated by multiplying the annual amount of mobile phone retired by the fractions (storage, reuse, collection, and others) obtained by the consumer survey. It was estimated that in 2007, more than 6.7 million mobile phones were collected by mobile telecommunication companies whereas more than 6.4 million were stored in households. As of 2007, more than 50 millions of used & end-of-life mobile phones were theoretically being stored in households for future disposal, based on this approach. This is much higher than the calculated number of 28 million mobile phones (as of 2006) by the consumer survey. During the period between 2000 and 2007, the estimated number of used & end-of-life mobile phones generated ranged from 7.7 million to 9.9 million each year (Table 3). A large fraction of the phones retired has been stored in households, while on average, about 8.7 million used & end-of-life mobile phones have been annually generated during this period. This indicates that an average generation rate of mobile phone waste in Korea over the past 8 years is estimated at 0.19 mobile phone/person/year (with a range of from 0.17 to 0.22). In the US, mobile phone subscribers have significantly increased from 340,000 in 1985 to 255 millions in 2007 (ITU, 2009). It was estimated that by 2005, approximately 135 million mobile phones weighing about 65,000 tons were retired annually in the US (Fishbein, 2002). Only 2.5 million phones out of the aforementioned 135 million mobile phones were collected for recycling or reuse in the United States during the period of 1999 through 2003 (Most, 2003). This indicates that only minimal amounts of the millions of phones have been collected each year. In Australia, more than 21.2 million mobile phone subscribers (or more than 95% of the population) exist in 2009 and replace their phones with new ones, on average, every 18–24 months (AMTA, 2009). It is estimated that more than 14 million end-of-life mobile phones and associated accessories are stored in offices and homes, waiting for disposal. In 2009, Australia collected 122 tons of mobile phone components including 806,000 handsets and batteries for recycling (AMTA, 2009). In Nigeria, a recent study shows that more than 32 million mobile phones will be retired by 2010. The study estimated that this volume of waste is equivalent to approximately 1800 tons of plastic, 15 tons of lead, and 124 tons of copper (Osibanjo et al., 2008).

4. Regulatory responses of used & end-of-life mobile phones management: extended producer responsibility (EPR)

As public attention regarding management electronic waste (e-waste) including mobile phone waste has increased worldwide, many efforts have recently been made to better manage the waste produced in Korea. In order to more effectively recover and process e-waste from consumers and to reduce its impact on the environment, the Korea Ministry of Environment (Korea MOE) promulgated the extended producer responsibility (EPR) regulation

Table 3
Estimated number of household storage and generation of used & end-of-life mobile phones per year in Korea (unit: 1000 units).

Year	Amounts of mobile phone retired	Household storage	Mobile phone waste generated			
			Reuse (loan or resold)	Collection by telecom company	Others (lost, disposal)	Total
2000	12,848	5178	1490	5422	758	7670
2001	13,121	5288	1522	5537	774	7833
2002	14,135	5696	1640	5965	834	8439
2003	16,619	6697	1928	7013	981	9922
2004	15,417	6213	1788	6506	910	9204
2005	13,749	5541	1595	5802	811	8208
2006	14,486	5838	1680	6113	855	8648
2007	15,993	6445	1855	6749	944	9548
Average	14,546	5862	1687	6138	858	8684

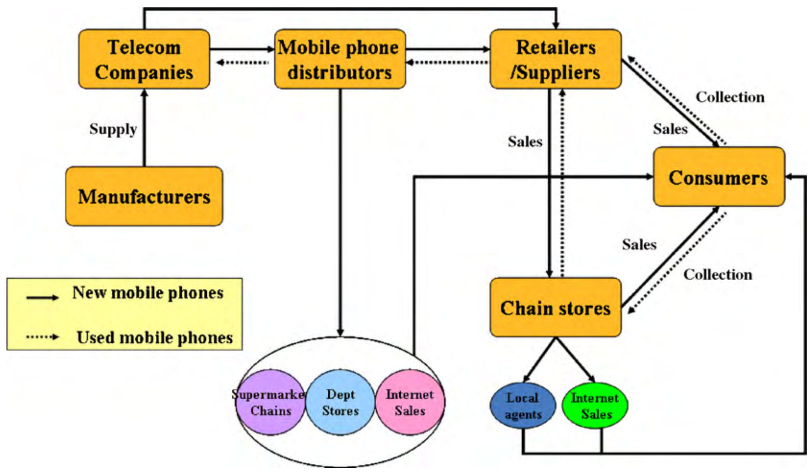

Fig. 4. Collection system of used & end-of-life mobile phones in Korea.

for a number of electrical and electronic products including televisions, personal computers, refrigerators, washing machines, and air conditioners in 2003. In 2005, mobile phones (including their associated batteries and chargers), fax machines, printers, copiers, and audio equipment were included in the EPR list (Korea MOE, 2005). The EPR is defined as the extension of the responsibility of producers for the entire product life cycle, and especially for their take-back, recycling, and disposal (Lindhqvist, 2000). It requires product producers to take extended responsibility for reducing potential environmental impacts of their products throughout their life cycle (from manufacturing to end-of-life). Ultimately, it provides an effective incentive to develop product designs that facilitate recycling and requires a more active role and participation in take-back programs. Thus, it is gaining popularity in environmental communities and agencies as a powerful strategy for product recycling and design changes because it gives producers physical and financial responsibility for taking back and recycling their products after consumers discard them (OECD, 2001).

On April 2, 2007, a new legislation, 'the Act on the Resource Recycling of Waste Electrical Electronic Equipment (WEEE) and End-of-life Vehicles (ELVs)' was adopted in an effort to further increase the focus placed upon e-waste by the previously mentioned EPR (Korea MOE, 2007). The WEEE Act is designed to reduce the amount of WEEE going to landfills and incinerators, to achieve higher recycling amounts of all targeted products by adopting the EPR policy, and to improve the overall environmental performance of electronic products during their life-cycle. This new legislation is the counterpart of the directives recently imposed by the European Union (e.g., WEEE directive, the restriction of the use of certain hazardous substances (RoHS) directive, and ELV directive) (EU Directive, 2000; EU Directive, 2002a,b). This indicates the ambitious goal of the Korea MOE to minimize all possible environmental impacts caused by WEEE and ELV disposal. It can also be thought of as the major regulatory response to the growing concerns about WEEE management in Korea. Producers, importers, distributors, and consumers all have a unique responsibility regarding the collection, treatment, recovery, and environmentally sound disposal of WEEE. For example, producers are required to finance the collection, recycling and disposal of WEEE. Additionally, hazardous substances should be absent or minimally present in the products in order to effectively achieve the recycling rates of WEEE imposed by the Act. Thus, the Act requires producers to phase out the use of six hazardous substances (i.e., cadmium, hexavalent chromium, lead, mercury, polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers) to design 'green' products, and to provide information on the components and hazardous substances present in electrical and electronic equipment for safe use and recycling as of January 1, 2008.

Ultimately, these recent regulation efforts encourage mobile phone producers to develop more environmentally sustainable products and require producers to take more responsibility for used & end-of-life mobile phones through a variety of collection programs. Restrictions on the use of toxic chemicals in mobile phones are critical for reducing potential environmental impacts when recycling and disposing of these units. This measure is expected to encourage producers to reduce or eliminate their use of toxic chemicals and find ways to better design mobile phones for reuse and recycling.

5. Collection and recycling of used & end-of-life mobile phones in Korea

5.1. Collection of mobile phone waste

Used & end-of-life mobile phones from consumers are mainly collected by local retailers and suppliers of mobile phones in Korea, as shown in Fig. 4. The local retailers and suppliers of mobile phones often recover an old product from consumers by offering economic incentives for the return of their used mobile phones when they purchase a new device. The trade-in price for old mobile phones depends upon the model of the phones, ranging mostly from 5 to 30 dollars. The local retailers and suppliers send the collected phones to the mobile telecommunication companies for reuse and export after refurbishment and repair, recycling, or final disposal. The retailers and suppliers are obliged to accept the old product without charge by the Act, beginning in 2008 (Korea MOE, 2007).

The material flow of used & end-of-life mobile phones in Korea is illustrated in Fig. 5. In addition to the collection by retail stores and suppliers, short-term collection programs and drives at department stores, train stations, and public schools offered mainly by the Korea AEE and governments have recently become available for the environmentally sound management of mobile phone waste. The mobile phones collected by these programs are usually recycled or refurbished and/or resold for domestic use. The phones sent to e-waste recycling facilities are processed for material recovery for secondary materials such as cobalt, copper, iron, and aluminum.

Fig. 6 shows the number of collected, reused, and exported used & end-of-life mobile phones in Korea during the period of year 2004–2007. The number of the collected, reused, and exported phones was obtained from the results of the expert surveys that were implemented in this study. Approximately five million mobile phones per year during this period were collected by the mobile

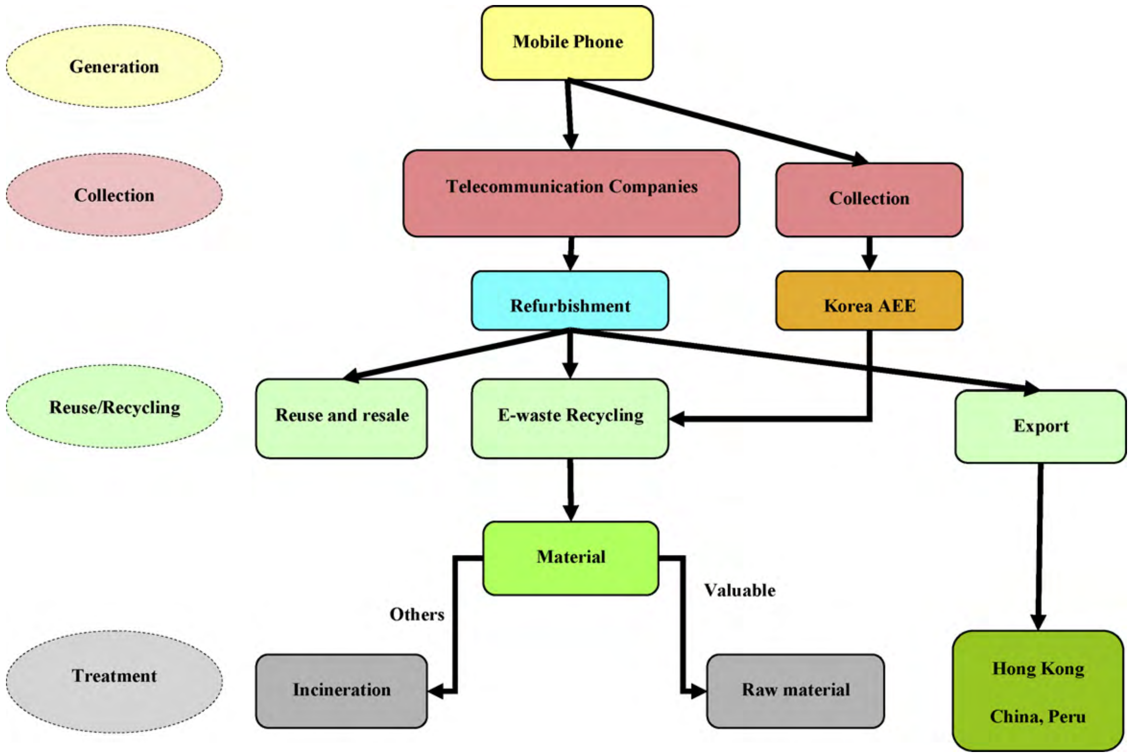

Fig. 5. Material flow of used & end-of-life mobile phones in Korea.

companies. The total collected numbers of mobile phones in 2005 and 2006 from Fig. 6 were similar to those of the collection estimated by the consumer survey results in Table 3. However, the amounts of the collected mobile phones by the telecommunication companies in 2004 and 2007 were lower than the estimated amounts of the collection by the consumer survey (Table 3). Several factors such as reuse and export market demands (especially in 2007), economic incentives to consumers, environmental regulations, and infrastructure for collection and recycling could affect the annual number of mobile phones collected by the mobile telecommunication companies. For example, the decreased collection rate in 2007 may have attributed to the decreased number of used mobile phones exported. In Table 3, it was assumed that the collection ratio of mobile phones (42.2%) by the telecommunication companies stays unchanged because of the data unavailability. This could likely be a result of the differences. Further work is still needed to characterize the differences in the periods, however.

Collection of the phones through mobile telecommunication companies, mobile retailers and other distribution channels should be the key element of an efficient collection system because such collection sites are convenient for consumers to bring their used mobile phones. The collection programs by the mobile telecommunication companies, the Korea AEE, and local governments have recovered only about 30% of the estimated number of used & end-of-life mobile phones retired in 2007 (Table 2). The majority of the collected and refurbished phones are either recycled for material recovery or sold to other countries such as China (via Hong Kong), Peru, USA, Singapore, and Vietnam. This may only be a temporary solution to the problem of mobile phone waste, as it avoids the disposal issue. However, care should be taken to ensure compliance with all applicable regulations, laws and technical standards before refurbishers and exporters ship and transport refurbished/used mobile phones, batteries and chargers. Dealers of used mobile phones for refurbishing and/or reselling have played a minor role in the current mobile phone collection system. They usually only accept relatively new models from the mobile telecommunication companies so that they can generate revenue from reselling collected mobile phones and their components, as well as charging fees to reuse market dealers, or exporters.

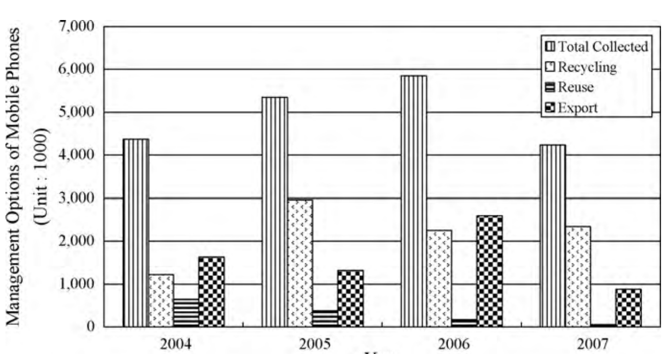

Fig. 6. The number of used & end-of-life mobile phones collected, recycled, reused, and exported in Korea.

5.2. Recycling processes of end-of life mobile phones

Recycling of obsolete mobile phones is an important subject area from economical and environmental viewpoints. Valuable elements or inorganic materials from the obsolete mobile phones and batteries such as ferrous, aluminum, cobalt, and copper can be recovered during material recovery processes. Recycling facilities already exist in Korea for many electronic devices such as computers and other consumer electronics. However, the recycling of mobile phones is still in an early stage in Korea in terms of recycling technology and infrastructure. This is partly due to the high cost of operating mobile phone recycling facilities, as well as the lack of a constant supply of used & end-of-life mobile phones.

Fig. 7 illustrates an example of the recycling processes of a mobile phone and its battery at one of the current mobile phone

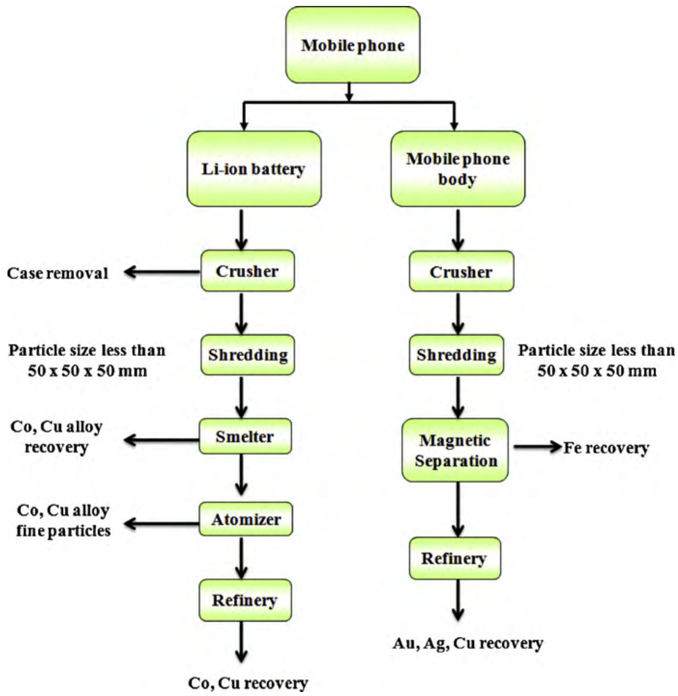

Fig. 7. Recycling processes of mobile phones and batteries at an e-waste material recycling facility in Korea.

waste recycling facilities in Korea. Recycling processes of used & end-of-life mobile phones are generally classified into the two separate processes: (1) recycling process for a mobile phone body part and (2) recycling process of a mobile phone battery. Printed circuit boards in mobile phone body parts are crushed and shredded to less than 50 mm size. The size-reduced particles are separated by magnetic separator to recover iron. The remaining materials are sent to a refinery for the recovery of copper and precious metals. In the recycling process of the mobile phone battery with lithium-ion, a series of mechanical processes, including shredding, smelting, atomizing, and refining are employed for the recovery of cobalt and copper alloy (Fig. 7). Since a mobile phone is diverse and complex in terms of components and materials, it is very important for recyclers to retain valuable materials and remove toxic substances, such as those in the batteries. Recycling technologies to recover secondary materials from printed circuit boards in mobile phones in Korea typically involve a pyrometallurgical process at copper smelters. In recent years an alternative combined method of mechanical pretreatment and hydrometallurgical process is employed for environmentally sound recycling technology to recover secondary metals from printed circuit boards. A major concern of the current recycling processes (e.g., dismantling, sorting and separation, smelting, or other recovering processes) is related to the uncontrolled emission of toxic chemicals (e.g., lead and PBDEs) to the surrounding environment. There are also potential health hazards from fumes, dusts, and harmful chemicals to workers who process the mobile phone components. Data regarding the emission of toxic air pollutants at mobile phone recycling facilities in Korea have yet to be determined.

6. Future challenges and suggestions

Over the past few years much effort has been made to better manage e-waste including mobile phone waste in Korea. Regulations and guidelines have recently been developed in order to establish an integrated e-waste management system. Since the EPR policy adopted by the Korea MOE has only recently started, the effectiveness of this policy cannot yet be determined. However, in this section, current and future challenges are acknowledged and several suggestions are made to improve the current management practices of mobile phone waste in Korea.

One of the major challenges to managing mobile phone waste is the need to establish proper and diverse collection systems for a stable supply of retired mobile phones, the avoidance of household storage, and the improper disposal. Take-back programs by producers and retailers have recently begun to collect used & end-of-life mobile phones from consumers. Thus far, collection programs by producers have not been successful to promote reuse or material recovery and recycling. However, a large number of used & end-of-life phones remain in household storage. One of the major reasons for the unsuccessful collection is related to a lack of consumer awareness. There is currently an insufficient body of public knowledge regarding the potential hazards that result from improper disposal of mobile phones (Jang et al., 2007). Another reason for household storage is that used & end-of-life mobile phones are commonly viewed as a potentially valuable resource and economic value by consumers (Jang and Kim, 2009). In addition, the legislation and infrastructure for efficient collection of used & end-of-life mobile phones from consumers have been lacking. There has been unclear physical and/or financial obligations and responsibility between stakeholders (producers, mobile telecommunication companies, local retailers and distributors) for the collection and management of used & end-of-life mobile phones in the EPR system.

More environmental initiatives should be promoted to raise consumer awareness of the importance of recycling and proper disposal. The awareness initiatives may include campaigns, education, and advertisements for the importance of mobile phone recycling, landfill and incineration bans on mobile phones, and recycling information included with new phones and phone bills. A variety of economic incentives should also be provided to consumers to withdraw used & end-of-life mobile phones stored in households. The examples of the economic incentives can include rebates and discounts on new products in exchange for a used mobile phone and financial incentives for consumers to donate their used & end-of-life mobile phones. Local retailers and suppliers should become actively involved in retrieving used & end-of-life mobile phones from consumers for an environmentally sound management. There is a need to offer convenient, permanent drop-off sites at high traffic locations within communities. Local governments should thus provide a variety of locations within the municipality where consumers can conveniently drop off their used mobile phones. These locations could include apartment complexes, shopping malls, supermarkets, banks, post-offices, and schools. Collection drives must be permanent and on-going. Such programs must be viable and sustainable to ensure credibility and consumer confidence.

A challenge associated with the collection program is that the mobile telecommunication companies have often failed to take extended responsibility for the final disposal of the phones because these responsibilities have not been clearly defined in the regulation. The companies should play a more vital role in addressing this issue. Mobile phone retailers and suppliers accept old mobile phones at free of charge for consumers when they buy new phones. Due to the lack of economic incentives for consumers, only a small fraction of the phones is being collected. Therefore, many obsolete mobile phones are stored in households. Consideration should be given to provide the incentives to consumers to involve the mobile phone collection system by the mobile telecommunication companies. Producers (or manufacturers), telecommunication companies, and retailers thus should consider the possibility of the physical and financial obligations for the collection and management of used & end-of-life mobile phones. Responsibility of each stakeholder (e.g., consumers, producers, retailers/suppliers, distributors, reuse market dealers, and exporters) must be more clearly defined and recognized in the EPR policy in the near future. A more effective EPR program with an increased collection and recycling mandatory target rates will create an incentive to remove obsolete mobile phones from storage among consumers who have easily access to inexpensive storage.

When compared to the mobile phones retired and generated in Korea, the total annual amount of the mobile phones recycled are still low. It is necessary to have a continuous and stable supply of mobile phone waste to establish a strong recycling industry. It would be especially valuable to study the potential economic benefits and the dynamics of the recycling market for mobile phone waste.

Lastly, by applying the principles of good product stewardship, mobile phones should be made with fewer toxic chemicals and designed with recyclability, compatibility, durability, and upgradeability in mind, thus rendering them more sustainable. Environmentally conscious design and manufacturing should be heavily fostered by manufacturers to reduce the potential impacts resulting from the improper disposal of mobile phones, as well as to consider material recovery and recycling at the end of a mobile phone's useful life.

Attempts have been made at finding a solution to environmentally sound management of end-of-life mobile phones worldwide. For example, representatives of the world's foremost manufacturers of mobile phones (e.g., Alcatel, LG, Matsushita, Mitsubishi, NEC, Nokia, Philips, SAMSUNG, Sharp Telecommunications Europe, Siemens, and Sony Ericsson) signed a declaration on sustainable partnership on environmentally sound management of end-of-life mobile phones under the Basel Convention (UNEP, 2006). The Mobile Phone Partnership Initiative (MPPI) was launched in 2002 and is expected to be model for partnership between the Convention and the mobile industry. By this partnership, a global system for end-of-life mobile phone can be made to achieve better product stewardship, promote the reuse, refurbishing/recycling options, and mobilize political and institutional support for environmental sound management. In recent years, in order to divert electronic waste from landfills, policy and legislation have been adopted in many developed countries, especially in the EU, based on the EPR principle. The EU's Waste Electrical and Electronic Equipment (WEEE) and the Restriction on Hazardous Substances (RoHS) Directives are typical examples (EU Directive, 2002a,b). The directives are aimed to assure efficient collection and sound management of electronic waste including mobile phones. In Australia, with the growing volumes of end-of-life mobile phones, MobileMuster, the recycling program of the mobile phone industry association designated as AMTA (Australia Mobile Telecommunication Association) works closely with local councils and community organization to promote and collect mobile phones for recycling. There are more than 3500 public drop-off points across the country (AMTA, 2009). Kahhat et al. (2008) recently proposed e-market for returned deposit paid by consumers to sellers at the time of purchase to ensure a proper end-of-life option while at the same time establishing a competitive market for better reuse and recycling services of electronic waste in the US.

7. Conclusion

This paper presents an overview of the current management practices of used & end-of-life mobile phones in Korea. Specifically, the generation rates, existing collection system, recent regulatory efforts, recycling processes, and challenges and suggestions for better management of used & end-of-life mobile phones have been discussed.

The number of retired mobile phone each year was estimated using the average lifespan of the device, information regarding mobile phone subscribers and domestic demands, and the results of a consumer survey. Our estimates indicate that an average of 14.5 million mobile phones is retired annually in Korea. This implies that the average generation rate of mobile phone waste in Korea was 0.19 mobile phones/person/year between the years 2000 and 2007. When comparing the number of mobile phones retired each year to the number disposed of, it becomes evident that a large proportion of used & end-of-life mobile phones is being stored in households waiting for disposal. According to our consumer survey, it was estimated that approximately 28 million used & end-of-life mobile phones were being stored at home as of the end of 2006. The average lifespan of a mobile phone was estimated to be 28 months.

According to the results obtained from this study, approximately five million used & end-of-life mobile phones have been collected by mobile telecommunication companies and producers each year between 2004 and 2007. Although various attempts to collect and process used & end-of-life mobile phones by the EPR program have recently started, there is still a lack of public awareness and proper collection system for the phones. Limited collection activities of obsolete mobile phones (e.g., special collection events by producers and local governments) have recently begun. More effective collection programs are still needed to reduce potential environmental impacts resulting from improper disposal of these phones.

Mobile telecommunication companies should be actively involved in the collection of used mobile phones, while producers should focus on proper treatment and recycling of the phones. There is a need to establish more cost-effective and advanced recycling technologies for obsolete mobile phones to accommodate the anticipated and cumulative increase over the upcoming years as well as to create economic profits for the recycling industry.

Improvements for the design and material selection of mobile phones are also required to recover precious metals and plastics at the end of mobile phone use by consumers. Collaborative efforts between producers, mobile telecommunication companies, consumers, and governments will be required to curb the growing mobile phone waste problem. Acknowledging the rapid increase of this problem, proper management for mobile phone waste should be one of the major priorities for regulatory agencies in addressing e-waste management concerns.

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References

Australian Mobile Telecommunications Association (AMTA). AMTA Annual Report; 2009. http://www.amta.org.au [accessed May 2010].

Basel Action Network (BAN). Mobile toxic waste: recent findings on the toxicity of end-of-life cell phones. A report by Basel Action Network; 2004.

CNET News. Cell phone sales hit 1 billion mark; 2008 February, http://www.news.cnet.com/8301-10784_3-9881022-7.html [accessed September 2009].

Choi H, Kim H. Social-cultural understanding of consumer behavior patterns for mobile phones, Research Report #05-07. Daejeon, Korea: Korea Information Strategy Development Institute; 2005 [in Korean].

Directive EU. 2000/53/EC of the European parliament and of the council of 18 September 2000 on end-of-life vehicles (ELV). Official Journal 2000;L269:0034–43.

EU Directive. 2002/96/EC of the European parliament and of the council of 27 January 2003 on the restriction of the use of certain hazardous substances in waste electrical and electronic equipment (RoHS). Official Journal 2002a;L037:0019–23.

EU Directive. 2002/96/EC of the European parliament and of the council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Official Journal 2002b;L037:0024–39.

Fishbein B. Waste in the wireless world: the challenge of cell phones. New York: INFORM Inc; 2002.

International Telecommunication Union (ITU). Information and communication technology statistics; 2009, http://www.itu.int/itd-d/ict-eye/reporting/indicators [accessed January 2010].

Jang Y, Kang H, Yoon H, Kim M, Kim Y. Collection system and management practices of used & end-of-life mobile phones. Final report submitted to the Korean Society of Waste Management, Seoul, Korea; 2007 [in Korean].

Jang Y, Kim M. A study of estimated economic values and cost-benefit analysis of used and end-of-life mobile phones. Korean Journal of Waste Management 2009;26(6):580–5.

Kahhat R, Kim J, Xu M, Allenby B, Williams E, Zhang P. Exploring e-waste management systems in the United States. Resources Conservation and Recycling 2008;52:955–64.

Korea Communications Commission (KCC). The number of mobile phone subscribers. Annual report (internal report); 2008.

Korea Association of Electronics & Environment (Korea AEE). http://www.aee.or.kr; 2009 [accessed May 2009].

Korea Ministry of Environment (Korea MOE). The act on the promotion of conservation and recycling of resources (revised by Korea MOE); 2005.

Korea Ministry of Environment (Korea MOE). The act on the resource recycling of waste electrical electronic equipment (WEEE) and end-of-life vehicles (ELVs); 2007.

Korean Statistical Information Service (KOSIS). Domestic demand for mobile phone; 2008, http://www.kosis.kr [accessed January 2009].

Lee B, Kwak J, Kim K, Kim S. Technical innovation and 3.5 mobile phone generation: lessons from Korea. Telecommunications Policy 2009;33:296–308.

Lincoln J, Ogunseitan O, Shapiro A, Saphores J. Leaching assessments of hazardous materials in cellular telephones. Environmental Science & Technology 2007;41(7):2572–8.

Lindhqvist R. Extended producer responsibility in cleaner production. Lund, Sweden: The International Institute for Industrial Environmental Economics, Lund University; 2000.

Liu X, Tanaka M, Matsui Y. Electrical and electronic waste management in China: progress and the barriers to overcome. Waste Management & Research 2006;24:92–101.

Long L, Yoo K, Lee J, Chung J. Milling process for recycling of waste mobile phones. Korean Journal of Applied Chemistry 2008;12:185–8 [in Korean].

Monteiro M, Moreira D, Chinelatto M, Nascente P, Alcantara N. Characterization and recycling of polymeric components present in cell phones. Journal of Polymers and the Environment 2007;15:195–9.

Most E. Calling all cell phones: collection, reuse, and recycling programs in the US. New York: INFORM Inc; 2003.

Musson S, Vann K, Jang Y, Mutha S, Jordan A, Pearson B, et al. RCRA toxicity characterization of discarded electronic devices. Environmental Science & Technology 2006;40:2721–6.

OECD. Extended producer responsibility: a guidance manual for governments. Paris: OECD; 2001.

Osibanjo O, Nnorom I. Material flows of mobile phones and accessories in Nigeria: environmental implications and sound end-of-life management options. Environmental Impact Assessment Review 2008;28(2/3):198–213.

Osibanjo O, Nnorom I, Ogbonna K. Modelling waste generation by the telecom sector in Nigeria: the grey side of the impressive outing. Waste Management & Research 2008;26(4):317–26.

Park H, Kim S. Telecommunication service usage as predictor of the timing of handset buyers' replacement purchases. Korean Journal of Marketing 2005;2:47–69 [in Korean].

Scharnhorst W, Althaus H, Classes M, Jolliet O, Hilty L. The end of life treatment of second generation mobile phone networks, strategy to reduce the environmental impact. Environmental Impact Assessment Review 2005;25:540–66.

Skerlos S, Morrow W, Chan K, Zhao F, Hula A, Seligar G, et al. Economic and environmental characteristics of global cellular telephone remanufacturing. In: IEEE international symposium on electronics and environment; 2003. p. 99–104.

Takamoro K, Tabuchi J, Watanabe M, Hirota Y. Development of battery pack for mobile phones. NEC Research & Development 2003;44(4):315–20.

UNEP. Mobile phone partnership initiative (MPPI). Guidance document: environmentally sound management of used & end-of-life mobile phone. The Basel Convention on the control of transboundary movements of hazardous waste and their disposal; 2006.

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SPECIAL FEATURE: ORIGINAL ARTICLE

Waste Management Research in Korea II

Yong-Chul Jang

Waste electrical and electronic equipment (WEEE) management in Korea: generation, collection, and recycling systems

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Abstract In Korea, generation of waste electrical and electronic equipment (WEEE), or electronic waste (e-waste), has rapidly increased in recent years. The management of WEEE has become a major issue of concern for solid waste communities due to the volumes of waste being generated and the potential environmental impacts associated with the toxic chemicals found in most electronic devices. Special attention must be paid when dealing with WEEE because of toxic materials that it contains (e.g., heavy metals, polybrominated diphenyl ethers, phthalates, and polyvinyl chloride). If managed improperly, the disposal of WEEE can adversely affect the environment and human health. Environmental regulatory agencies; electronic equipment manufacturers, retailers, and recyclers; environmental nongovernmental organizations; and many others are much interested in updated statistics with regard to how much WEEE is generated, stored, recycled, and disposed of. In Korea, an extended producer responsibility policy was introduced in 2003 not only to reduce the amount of electronic products requiring disposal, but also to promote resource recovery from WEEE; the policy currently applies to a total of ten electrical and electronic product categories. This article presents an overview of the current recycling practices and management of electrical and electronic waste in Korea. Specifically, the generation rates, recycling systems and processes, and recent regulations of WEEE are discussed. We estimated that 1263000 refrigerators, 701000 washing machines, 1181000 televisions, and 109000 air-conditioning units were retired and handled by the WEEE management system in 2006. More than 40% of the products were collected and recycled by producers. Four major producers' recycling centers and other WEEE recycling facilities are currently in operation, and these process a large faction of WEEE for the recovery of valuable materials. Much attention should still be paid to pollution prevention and resource conservation with respect to WEEE. Several suggestions are made in order to deal with electronic waste management problems effectively and to prevent potential impacts.

Key words WEEE · Electronic waste · e-waste · Recycling system · EPR

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Introduction

The republic of Korea, with a population of over 48 million people, has a high environmental pollution loading due to its rapid industrial development and high population density. The rapid growth of Korean electronics manufacturers (e.g., Samsung, LG, and Daewoo) and the information technology industry in Korea has become the major driving force for the expansion of domestic markets for electronic products. The production and sale of home appliances and electronic devices have rapidly increased over the past two decades. Recent statistics show that as of 2006, more than 35 million mobile phones, 22 million televisions, and about 13 million personal computers were in use in Korea, as shown in Fig. 1.[1] More than 75% of the total population use the Internet.[2] As liquid-crystal-display (LCD) and plasma-display-panel (PDP) televisions replaced cathode-ray-tube (CRT) televisions, domestic demand for all televisions in 2006 increased to about 2.4 million in Korea.[1] As of 2008, there were more than 45 million mobile phone subscribers, and approximately 19 million mobile phones were sold in Korea in 2007.[1,3]

When electrical and electronic products reach the end of their useful life, they become waste electrical and electronic equipment (WEEE), which is often referred to as electronic waste (or e-waste for short). Waste electrical and electronic streams encompass a wide range of electrical and electronic waste products, including home appliances (e.g., refrigerators, washing machines, and air conditioners); information technology and telecommunication equipment (e.g., personal computers, laptop computers, printers, copying equipment, calculators, facsimiles, telephones, and

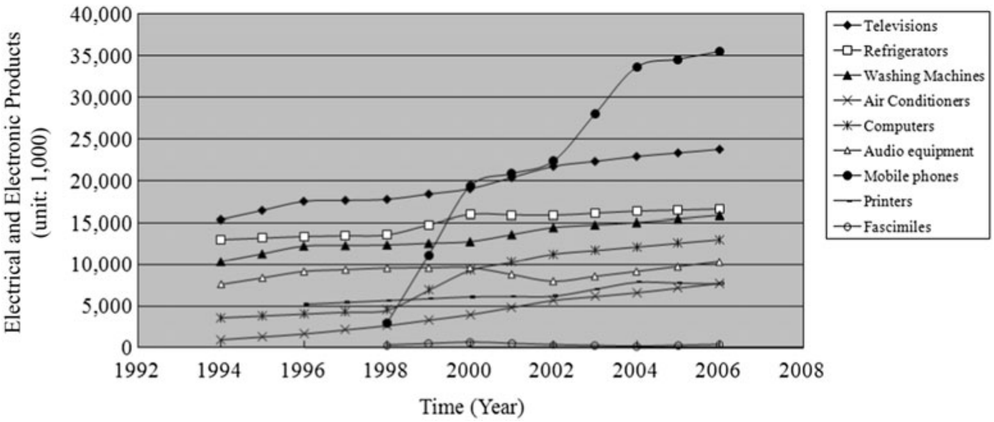

Fig 1. Number of electrical and electronic products in use in households in Korea

mobile phones); consumer electronic devices (e.g., televisions, radios, video cameras, and audio equipment); and other household electrical and electronic equipment (e.g., vacuum cleaners, toasters, coffee machines, hair dryers, watches, and irons). The categories and scope of WEEE may vary depending on the definition and regulations of the waste stream in a given country. The detailed definition and categories of WEEE are discussed in a later section. In this article, the terms "WEEE" and "e-waste" are synonymously and interchangeably used, although WEEE is a more broad definition and refers to all electrical and electronic wastes generated by consumers, including home appliances, information technology and telecommunication equipment, and consumer electronic devices. E-waste is often considered to be a subcategory of WEEE and indicates "electronic" products that are discarded by consumers.

Electrical and electronic waste represents one of the fastest growing solid waste streams in Korea. In many parts of the world, the large consumer demand for newer electronic products and the advanced development of information and communication technology (ICT) have resulted in tremendous amounts of WEEE that are disposed of. The disposition and management of WEEE is an emerging environmental issue of concern for the solid waste communities in Korea and around the world. The lifespan of electronic devices is becoming shorter, and so the quantity of WEEE is expected to increase. For example, the lifespan of personal computers has decreased from 4–6 years to often less than 2 years at present. In 2004, more than 180 million personal computers were sold worldwide, while 100 million computers were estimated to be obsolete, with some recycled to recover materials.[4] A recent study reported that approximately 130 million mobile phones were retired in the United States in 2005, with a cumulative estimate of more than 700 million phones already discarded or stockpiled prior to disposal.[5] In Canada, approximately 23500 tons of information technology equipment, such as personal computers, notebook computers and peripherals, were disposed of in 2005.[6] Sales of notebook computers have substantially increased over the past decade, and so the number of notebook computers discarded will increase in the waste stream.

In addition to the difficulties caused by the vast amount of WEEE produced, there is a risk posed by the myriad of toxic chemicals present in WEEE, including metals (e.g., arsenic, cadmium, chromium, copper, lead, and mercury) and organic chemicals (e.g., polybrominated diphenyl ethers as flame retardants, phthalates, and polyvinyl chloride). Thus, concerns have been raised that toxic chemicals could leach from these wastes when improperly disposed of or handled.[7–13] The composition and amount of toxic chemicals found in WEEE largely depend on factors such as the type of electronic device and the model, manufacturer, and date of manufacture. For example, printed circuit boards found in most electronic devices may contain arsenic, cadmium, chromium, lead, mercury, and other toxic chemicals. Typical printed circuit boards treated with lead solder in obsolete electronic devices have been reported to contain approximately 50 g of tin–lead solder per square meter of circuit board.[14] Cathode ray tubes in computer monitors and televisions may contain barium, cadmium, copper, lead, zinc, and other rare earth metals. In cathode ray tubes, leaded glass provides shielding from X-rays generated during the picture projection process. A color cathode ray tube typically contains 1.6–3.2 kg of lead on average.[15] With a growing concern regarding the leaching of lead and other metals, several states in the US recently banned cathode ray tubes from landfills because of their toxic characteristics.[16,17]

The toxic chemicals from many electronic devices can be released into the environment and could pose a significant threat to human health via recycling and uncontrolled treatment processes.[8,13,18] The disposal of WEEE with the rest of the municipal solid waste (MSW) stream in a landfill may result in negative impacts on the environment (e.g., groundwater contamination by lead leaching and high concentrations of lead in landfill leachate). When WEEE is burnt in incinerators, heavy metals become concentrated in the ash, limiting its disposal and reuse options. Since most of the plastic materials in WEEE contain flame retardants that are mainly halogenated organic chemicals, toxic organic contaminants such as dioxins and furans may be formed during incineration and exit through the stack to the surrounding area in the form of gaseous pollutants. Thus far, limited knowledge exists regarding the extent to which management of WEEE via traditional waste management systems, such as landfilling and incineration, has caused adverse impacts on the environment.[19–22]

In response to growing concern, many parts of the world are trying to seek environmentally sound and economically feasible models for WEEE management. Many countries have shown great interest in establishing recycling processes to reduce the quantity of WEEE to be disposed of and to recover valuable resources. Unlike that for municipal solid waste, the WEEE management system is not well established in most countries. A number of studies have been recently published to provide current knowledge and/or to address potential problems associated with WEEE management.[10,23–29]

This article presents an overview of the current recycling practices and management of WEEE in Korea. The generation rates of WEEE in Korea have been estimated. Also discussed are the historical and recent regulatory efforts regarding WEEE recycling with an emphasis on the extended producer responsibility (EPR) policy, which was introduced in 2003 in Korea. The current collection system, material flow, and recycling rates of WEEE are presented, followed by the processes at existing electronic waste recycling facilities. Finally, suggestions are made for establishing environmentally sound recycling and management systems of WEEE in Korea.

Methodology

The methodology of this study included gathering data associated with annual domestic demands (or sales) of selected home appliances and electronic devices, site visits, questionnaire surveys, interviews and conversations, and a review of the available literature. The devices covered in this article are mainly televisions, refrigerators, washing machines, air conditioners, personal computers, audio equipment, mobile phones, printers, copying machines, and facsimiles. The annual domestic demands of the products were obtained from the Bureau of Statistics in Korea. Statistical data regarding the amount of retired WEEE were obtained by using surveys, previous research reports, statistical data from the governmental sector, and scientific articles.[1,3,29–32] Site visits to local electronics retailers, private reuse market dealers, WEEE recycling centers and facilities, and the Korea Association of Electronics and Environment (Korea AEE) were carried out to support and supplement information gathered by the surveys. The Korea AEE, a producer responsibility organization (PRO), was established in 2000 as a cooperative effort to share the responsibility of environmentally sound WEEE recycling between the electronic industry and its members. WEEE recycling processes were examined during the facility visits. The results of the questionnaire surveys regarding the patterns and rates of consumption and disposal of electronic devices by consumers, retailers, and local governments were used to estimate the generation rate of the selected WEEE categories. Interviews and conversations with environmental regulatory agencies, recycling industry experts, and PRO committees were conducted to obtain details of recent progress and development associated with WEEE management. The available literature was reviewed to allow comparisons to be made with the collection and recycling of WEEE in other countries and regions.

Definition and generation of WEEE in Korea

Definition and scope of electrical and electronic equipment

Since numerous electrical and electronic devices are being used in our modern society, it is important for the solid waste community to recognize how to define and classify the devices according to the laws and regulations as part of waste management practices. There is no widely accepted definition of discarded electrical and electronic devices around the world. In most cases, electronic waste (or e-waste) is used as a generic term to describe obsolete or end-of-life (EOL) electronic devices and comprises the relatively expensive and durable products used for information processing, telecommunications, or entertainment in households and businesses.[28] E-waste refers to all electronic devices used by consumers that are discarded and not intended for further use. It generally consists of many different types of electronic devices such as televisions, personal computers and monitors, laptop computers, mice, keyboards, printers, scanners, copy machines, facsimiles, telephones, mobile phones, audio equipment, and video cameras. In recent years, high-definition liquid-crystal-display televisions, mobile phones, computers, portable digital assistants, and MP3 players have experienced rapidly increasing sales and are replaced frequently.

WEEE is another term that is often used interchangeably with e-waste, but includes a greater variety of home appliances and electrical equipment (e.g., refrigerators, washing machines, air conditioners, vacuum cleaners, toasters, coffee machines, hair dryers, watches, and irons). In Europe and in many other regions and countries, WEEE is a commonly used regulatory and technical term and includes electrical and electronic items that are widely used in the home. According to the European Union (EU) WEEE directive, WEEE is specifically defined as electrical and electronic equipment which consumers dispose of or are required to dispose of pursuant to the provisions of national law, including all components, subassemblies, and consumables.[33] In the EU directive, WEEE consists of ten categories and covers a total of 96 device types or pieces of equipment, including large and small home appliances, information technology and telecommunications equipment, lighting equipment, medical devices, automatic dispensers, and others categories.[33] In Japan, the Law for Recycling Home Appliances was enacted in June 1998 to establish a recycling framework that places the obligation for handling waste items on the manufacturers and retailers of home appliances. A recent study discussed the Japanese system for recycling waste home electrical appliances.[34]

Table 1. Definition and scope of waste electrical and electronic equipment (WEEE) or electronic waste[27,28,33–35]

Country	Term	Scope	Types of device or equipment
EU	WEEE "Electrical or electronic equipment (EEE) which is waste, including all components, subassemblies and consumables that are part of the product at the time of discarding."	Large home appliances	Refrigerators, washing machines, dish washing machines, microwaves, electric heaters, air conditioners
		Small home appliances	Vacuum cleaners, toasters, coffee machines, hair dryers, watches, irons, and other appliances
		IT and telecommunications equipment	Personal computers, laptop computers, printers, copying equipment, calculators, facsimiles, telephones, mobile phones
		Consumer equipment	Radios, televisions, video cameras, audio amplifiers,
		Lighting equipment	Fluorescent lamps, high-density discharge lamps
		Electrical and electronic tools	Drills, saws, sewing machines, tools for screwing, welding equipment, mowers and gardening equipment
		Toys, leisure and sports equipment	Video games and consoles, electric trains and car racing sets
		Medical devices	Radiotherapy equipment, dialysis, pulmonary ventilators
		Monitoring and control instruments	Smoke detectors, thermostats, heating regulators
		Automatic dispensers	Automatic dispensers for hot drinks, solid products, bottles or cans, automatic dispensers for money
Korea	WEEE	Limited electrical equipment and electronic devices	Refrigerators, washing machines, air conditioners, PCs, televisions, audio equipment, mobile phones, printers, copy machines, facsimiles
Japan	WEEE	Home appliances	Refrigerators, washing machines, air conditioners, televisions
China	WEEE, same definition as the EU Directive	Limited electrical equipment and electronic devices	Refrigerators, washing machines, air conditioners, personal computers, televisions
US	Electronic waste (or e-waste)	Electronic products that are discarded by consumers	Televisions, computer monitors, computers and computer peripherals, audio and stereo equipment, VCRs and DVD players, video cameras, telephones, mobile phones, fax and copy machines, video game consoles

Table 1 presents the definitions and scope of WEEE or electronic waste.[27,28,33–35] Although a clear distinction between e-waste and WEEE may be difficult to achieve, it is important to understand that one should be cautious of using the exact definition and category of the terms e-waste and WEEE.

In Korea, WEEE is the more commonly used and preferred term, and it was recently defined as "any electrical or electronic devices that are no longer in use and have been discarded by consumers" by the Act on Resource Recycling of Waste Electrical Electronic Equipment (WEEE) and End-of-life Vehicles (ELVs).[35] The Act was enacted in April 2007; it will be further discussed in a later section. Unlike the classification of WEEE in the EU, the category and type of WEEE in Korea is currently very limited and includes a total of ten types of electrical and electronic devices (i.e., refrigerators, washing machines, televisions, air conditioners, computers, printers, facsimiles, audio equipment, copy machines, and mobile phones), as shown in Table 1. As regulations strengthen, this list may be expanded and updated in the future. This study primarily discusses the generation and management of such devices in Korea.

Other common terms associated with WEEE may include "end-of-life (EOL) electronics" and "discarded consumer electronic devices (CEDs)." The terms "white goods" (e.g., washing machines, refrigerators, and ovens) and "brown goods" (e.g., Televisions, computers, and radios) have also been used for dealing with specific categories in electronic and electrical waste streams.

Generation of WEEE in Korea

In order to develop proper WEEE management strategies, it is important to characterize the quantities and composition of WEEE. The quantities and composition can be influenced by several factors, including economic conditions, availability of a reuse market, infrastructure of the recycling industry, waste segregation programs, and regulation enforcement. Unlike municipal solid waste, only limited studies have been carried out to estimate the generation of WEEE in Korea.[29–32] It should be noted that the estimated number of retired WEEE items should not be equated with the amount of generated WEEE. In this article, the word "retired" refers to WEEE that has reached the end of its useful life. The retired number represents what is theoretically available for waste collection and recycling. Some fraction of these products that have been retired is resold or loaned to others, or is stored at households and is destined to enter the WEEE stream at a later date. When WEEE is collected, reused, recycled, treated, and disposed of, it is referred to as having been "generated."

The estimation method of the amount of WEEE generation is usually based on domestic demand for electrical and

Table 2. Generation of selected WEEE categories (in thousands of units) in Korea[1,29,30]

Year		Refrigerators	Washing machines	TVs	Air conditioners	Total
2004	Amount of device in use	23851	15068	22910	6615	68444
	WEEE retired from businesses and households	1336	814	1581	152	3883
	WEEE retired from households	1122	700	1281	102	3205
	WEEE stored/loaned	220	76	336	18	650
	Estimated waste generation	902	624	945	84	2555
2005	Amount of device in use	25406	15500	23350	7210	71466
	WEEE retired from businesses and households	1423	837	1611	165	4036
	WEEE retired from households	1195	720	1305	110	3330
	WEEE stored/loaned	234	78	342	19	673
	Estimated waste generation	961	642	963	91	2657
2006	Amount of device in use	26849	15905	23758	7752	74264
	WEEE retired from businesses and households	1515	859	1639	178	4191
	WEEE retired from households	1263	701	1181	109	3254
	WEEE stored/loaned	250	81	348	21	700
	Estimated waste generation	1013	625	873	89	2600

electronic products and their average lifespan (i.e., the length of the time between the initial purchase of an electronic device and the time it completes its useful life). Lifespans of devices vary depending upon the type of device, economic and market conditions, customer age group (or generation), and cultural behavior. It was estimated in 2006 that the average lifespans were 7.7 years for refrigerators, 7.6 years for washing machines, 7.3 years for televisions, and 6.0 years for air conditioners.[30] Shorter lifespans of 4.0 years were found for computers, 4.3 years for printers, and 2.4 years for mobile phones.[30,32] By combining the sales data and applying lifespan assumptions for each product, the annual units (or sometimes the corresponding weight) of a product that is retired and undergoes waste management via reuse and refurbishment, recycling, export, or disposal are predicted (i.e., the amount of WEEE retired). The estimated amount of WEEE generated was determined from the retired amount of WEEE by subtracting the volume of WEEE that is reused, loaned, or stored at households. The proportions of items reused, loaned, or stored in the household have been estimated using a consumer survey.[30]

The estimated numbers of selected electronic appliance categories that were retired and the waste generated between 2004 and 2006 are shown in Table 2. During these years, the quantity of selected WEEE generated each year was approximately 2.6 million units (Table 2). Refrigerators were the largest contributor and accounted for nearly 40% of the selected WEEE items, followed by televisions and washing machines. As shown in Table 2, more than 74 million units of televisions, refrigerators, washing machines, and air conditioners were in use in households in 2006. During the same year, the total number of these four products retired was approximately 4.2 million units. By considering the common usage patterns of many other home appliances, the annual number of the products to be retired and generated is projected to continually increase due to increasing sales and decreased lifespans of the devices. Details on the data resources, assumptions, and calculations underlying the generation estimates can be found elsewhere.[31]

Assuming a standard weight for each product type (31 kg for televisions, 67 kg for refrigerators, 48 kg for washing machines, and 67 kg for air conditioners), then 131 000 tons of the selected WEEE categories was generated in 2006, representing approximately 0.72% of the municipal solid waste stream in Korea (calculated on the basis of 18 million tons of municipal solid waste generation in 2006). This corresponds to approximately 2.7 kg of selected WEEE/capita/year (based on an assumed Korean population of 48 million).

In Japan, more than 22 million televisions, refrigerators, washing machines, and air conditioners were estimated to be have been generated as waste in 2005.[36] Approximately 7.5 million used computers were generated in Japan in 2004.[37] In China, a recent study showed that in 2005, the estimated numbers of obsolete refrigerators, washing machines, televisions, air conditioners, and computers were 9.8, 7.6, 33.5, 0.65, and 4.5 million units, respectively. The total mass of obsolete units of these five selected WEEE categories was estimated to be about 1.76 million tons in China in 2003. In 2010, the annual number of these units retired is estimated to be 105 million.[24,27] In the US, it was estimated that between 1980 and 2004 as many as 180 million units of televisions, computers, computer peripherals, and cell phones were still in storage awaiting disposal. Among these, televisions and computers accounted for 34% and 52%, respectively.[38] Another study estimated that over 315 million computers would reach the end-of-life stage in the US by 2003.[39] An industry research report showed that approximately 270 million electronic items (computers, televisions, VCRs, mobile phones, and monitors) were removed from US households in 2005.[40] According to the US EPA, approximately 1.4–1.7 million tons of the devices were primarily disposed of in landfills, and only 0.31–0.34 million tons were recycled in 2005 in the US.[38]

Regulatory responses to WEEE in Korea: extended producer responsibility (EPR) and the laws relating to WEEE

In response to the increasing volumes of WEEE and their potential environmental impacts through various disposal pathways, several measures and regulations have been developed to properly manage such waste in Korea. Korea's

Table 3. Target recycling rates and the amount of WEEE handled (in tonnes) by the extended producer responsibility (EPR) system in Korea[43]

Type of WEEE	2006			2007			2008		
	Domestic demand	EPR target rate	Amount recycled by producers	Domestic demand	EPR target rate	Amount recycled by producers	Domestic demand	EPR target rate	Amount recycled by producers
Refrigerators	91 007	11 467	14 568	85 956	11 432	18 957	95 107	13 790	18 657
Washing machines	260 950	44 101	44 645	261 575	45 252	50 832	230 796	43 620	53 535
Televisions	94 899	22 206	22 200	98 794	23 908	23 908	79 759	20 179	22 034
Air conditioners	135 882	2 310	2 211	130 303	2 475	2 906	116 105	2 438	2 431
Computers	43 193	4 060	4 934	46 399	4 547	6 061	83 186	8 567	9 906
Audio	2 410	306	377	1 979	259	403	5 985	891	1 169
Mobile phones	2 928	451	451	2 836	468	468	3 146	566	710
Copying machines	5 748	483	1 293	4 130	388	493	3 838	487	497
Facsimiles	1 250	105	110	1 012	95	171	720	82	110
Printers	21 065	1 769	1 771	12 290	1 130	1 551	10 996	1 231	1 231

first law to regulate WEEE, the Act on the Promotion of Conservation and Recycling of Resources (also called the Waste Recycling Act), took effect in 1992. Two home appliance categories, televisions and washing machines, were first regulated by the Act, and air conditioners and refrigerators were included in 1993 and 1997. The Korea Ministry of Environment (Korea MOE) introduced the Waste Deposit-Refund System for limited categories of home appliances, packaging materials (e.g., glass, plastics, and cans), and other items (e.g., lubricating oil, batteries, tires, and fluorescent lamps) as part of the Act in 1992.[41] The "recycling fee" was deposited by manufacturers (or producers) and importers based on the annual production of their products in the deposit-refund system. When they collected and recycled their obsolete products, the deposited money was refunded to them in proportion to the product numbers they recycled. Money that was not refunded was contributed to the collection and recycling system for the waste materials. The objectives of the system were to reduce the environmental burden caused by the disposal of recyclable products and to encourage producers to recycle their products that have reached the end-of-life stage. However, it was not successful in encouraging collecting and recycling of waste materials because of low economic incentives to the producers. For some of the products, manufacturers often had to pay more to recycle their waste materials than the money they deposited.

In 2003, the MOE modified the Waste Recycling Act to promote effective collection and recycling of waste materials and promulgated an extended producer responsibility (EPR) regulation for the items covered by the Waste Deposit-Refund System and for personal computers and monitors.[42] EPR involves producers taking more responsibility for managing the environmental impacts of their products throughout their lifecycle. Producers that manufacture the EPR products must collect and recycle an assigned quantity based on a certain percentage of their annual production volume. If this is not achieved, they must pay more than the cost of recycling the waste products. Mobile phones and audio equipment were included in the EPR list in 2005, while printers, facsimiles, and copying machines were included in 2006.

In 2007, new legislation, the Act on the Resource Recycling of Waste Electrical Electronic Equipment (WEEE) and End-of-life Vehicles, was enacted.[35] The Act is aimed at reducing the amount of WEEE going to landfills and incinerators, achieving a high recycling rate for all targeted products by adopting the EPR policy, and improving the overall environmental performance of electronic products during their lifecycle. This new legislation is the counterpart of EU directives such as the WEEE directive,[33] the restriction of use of certain hazardous substances (RoHS) directive,[43] and end-of-life vehicle (ELV) directive.[44] This underlines the overall ambition of the Korea MOE to minimize all possible environmental impacts caused by WEEE disposal. It should be thought of as a major response to growing concerns about the WEEE management issue in Korea. Producers, importers, distributors, consumers, and all other parties should be involved in the collection, treatment, recovery, and environmentally sound disposal of WEEE. Producers are required to finance the collection, recycling, and disposal system of WEEE.

Table 3 presents the target and actual recycling rates of WEEE under the EPR policy in Korea between 2006 and 2008.[45] The annual mandatory recycling rate of each product is determined by the Korea MOE, based on the target recycling rates over the previous 2 years, the amount of electrical and electronic products shipped from the warehouse, and the recycling market conditions. The total amount of the EPR mandatory recycling is determined by the annual amount of electrical and electronic products shipped from the warehouse multiplied by the annual mandatory recycling rate. In 2008, the weights of items to be recycled under the EPR scheme as determined by the Korea MOE were 43 620 tons for refrigerators, 20 179 tons for televisions, 13 790 tons for refrigerators, and 2438 tons for air conditioners. The amounts of all the EPR products recycled by producers with the exception of air conditioners exceeded their mandatory target rates. This indicates that the recycling of WEEE has been successfully performed as a result of the implementation of the EPR system.

In order to effectively achieve the recycling rates of WEEE imposed by the Act, hazardous substances should be absent or minimally present in the products. The Act also

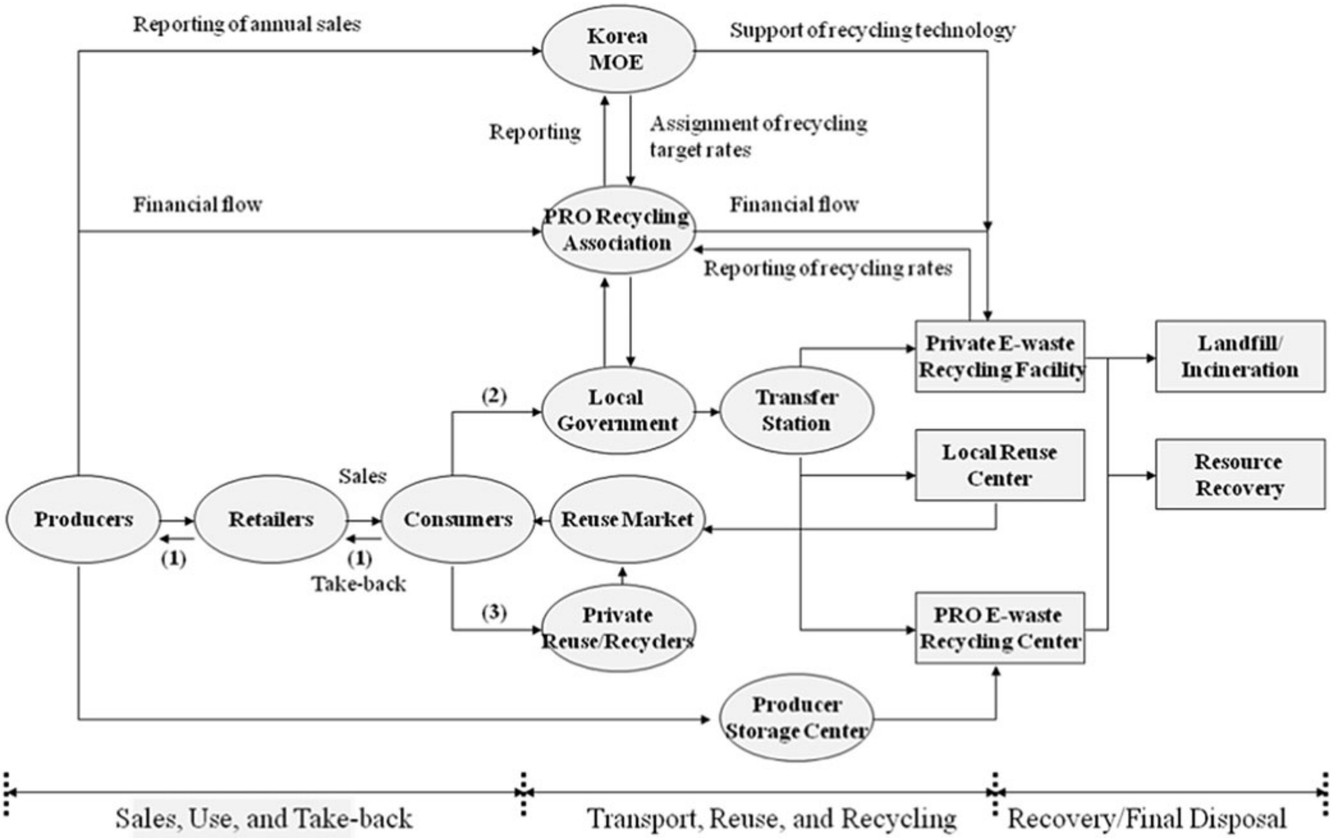

Fig 2. Waste electrical and electronic equipment (WEEE) collection and recycling system in Korea. *MOE*, Ministry of Environment; *PRO*, producer responsibility organization; *1–3*, the three major collection pathways

requires producers to phase out the use of six hazardous substances (i.e., cadmium, hexavalent chromium, lead, mercury, polybrominated biphenyls, and polybrominated diphenyl ethers), to design "green" products, and to provide information on the components and hazardous substances present in electrical and electronic equipment for safe use and recycling as of January 1, 2008.

Recent WEEE regulation efforts, along with strict enforcement, should increase collection and recycling rates of WEEE through diverse collection programs, encourage manufacturers to develop more environmentally sustainable products, and require manufacturers to take extended responsibility for the recycling of their products. Restrictions on the use of the six aforementioned toxic chemicals in electrical and electronic products are critical for reducing potential environmental impacts during recycling and disposal. This measure should encourage manufacturers to reduce or eliminate their use of toxic chemicals and to design electronic devices compatible with reuse and recycling.

Collection and recycling systems of WEEE in Korea

Collection systems of WEEE

WEEE from consumers is typically collected via three major pathways in Korea, as shown in Fig. 2. The first pathway is that electronic equipment producers, retailers, or suppliers usually take an old product from consumers free of charge when they purchase a similar new product (designated as (1) in Fig. 2). Producers, retailers, and suppliers are obliged to accept the old product and subsequently to transport it to producer storage centers. There are approximately 60 WEEE storage centers around the country that have been established by a number of manufacturers and importers of consumer electronics. Waste products are ultimately sent to producer recycling centers for material and resource recovery.

The second pathway involves local governments collecting end-of-life electronic equipment from households at designated areas or curbside collection points near residential complexes (designated as (2) in Fig. 2). Under this system, households have to buy a yellow sticker from the local government, stick it on the device, and place it in the designated area for obsolete electronic devices. The disposal fee ranges usually from US$3–10 per device, depending on the type of electronic device. Local transporters contracted by local governments pick up the discarded electronics on a weekly basis and send them to either private WEEE recycling facilities, producer recycling centers, off-site treatment facilities, or local reuse centers.

Private collectors play a minor role in the WEEE collection system and often pay consumers for some electronic items (e.g., computers, televisions, and air conditioners)

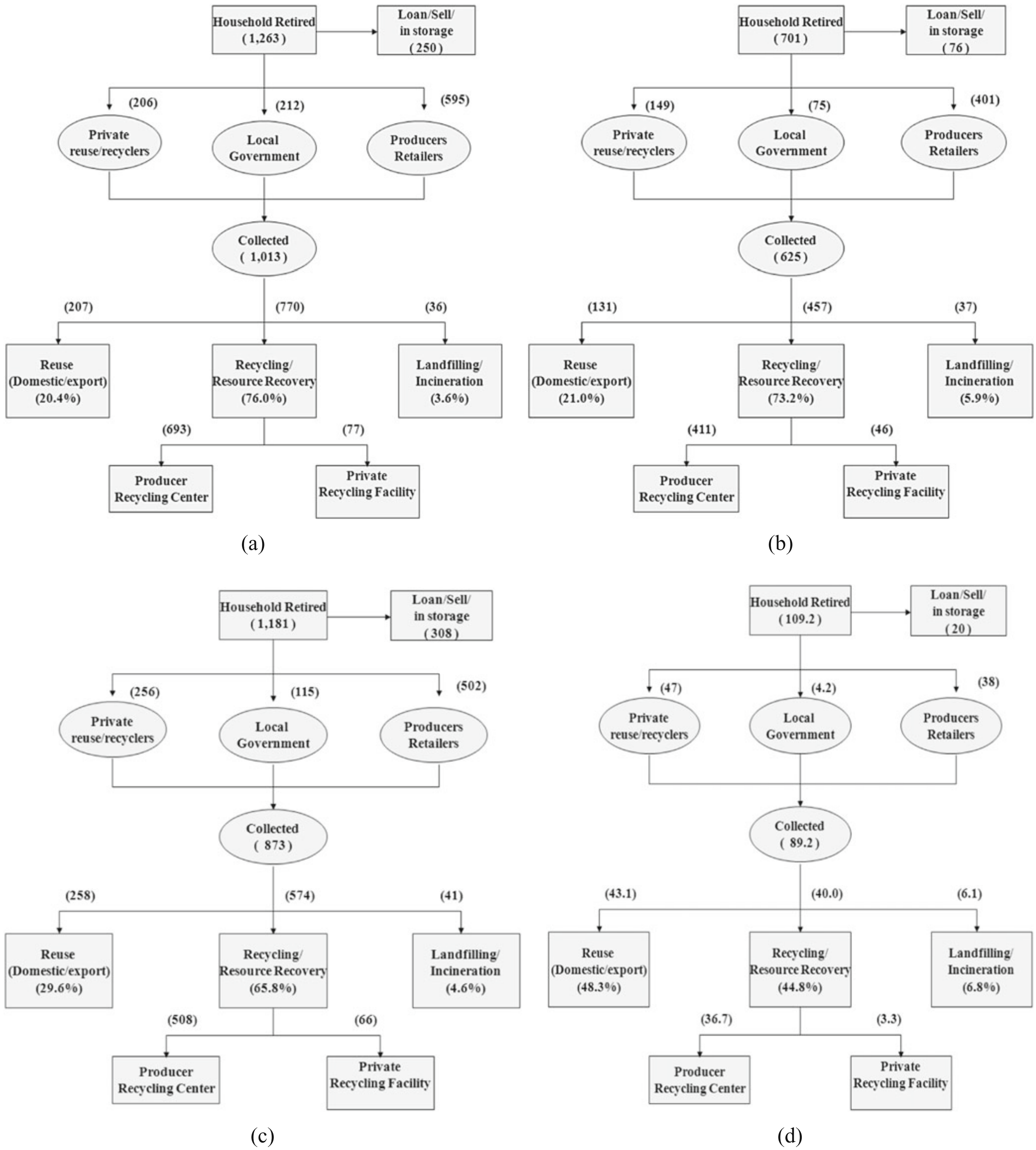

Fig 3. Material flow (in thousands of units) of selected WEEE categories: **a** refrigerators, **b** washing machines, **c** televisions, and **d** air conditioners in Korea in 2006

(designated as (3) in Fig. 2). They can generate revenue from reuse market dealers, private recyclers, or exporters by selling their collected electronic items and components.

Figure 3 shows the material flow of the selected WEEE categories (refrigerators, washing machines, televisions, and air conditioners) by the three major collectors (producers, local governments, and private collectors and recyclers). A large proportion of each product is collected by producers/retailers, as shown in Fig. 3. Increased collection rates can be attributed to the implementation of EPR regulations. Collection activities of WEEE by local governments have been limited partly because of the lack of public awareness

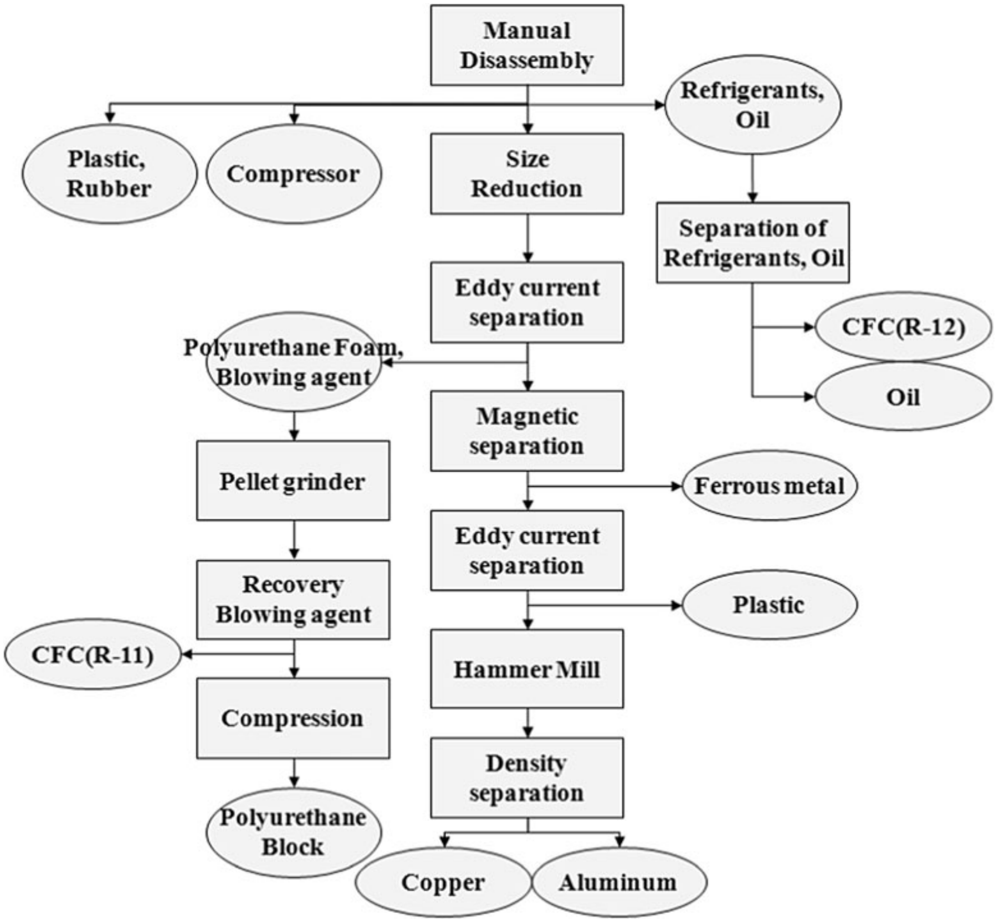

Fig 4. Recycling processes for televisions, refrigerators, washing machines, and air conditioners at producers' electronic waste recycling centers in Korea. *CFC*, chlorofluorocarbon

regarding the importance of proper disposal of WEEE as well as the lack of the establishment of an effective WEEE collection network by municipalities. In addition, some obsolete electronic devices are commonly viewed as potentially valuable resources by residents. Only small amounts of the selected WEEE categories are landfilled or incinerated as shredded residues because landfilling and incineration of WEEE is commonly not accepted by local governments in Korea.

Recycling systems and processes of WEEE

Recycling of WEEE is important not only to reduce the amount of the waste requiring proper treatment and disposal, but also to promote the recovery of valuable resources. Valuable materials from obsolete electrical and electronic devices include ferrous metals, aluminum, and copper and can be recovered during material recovery processes at electronic waste facilities. In recent years, many developed countries have shown a great interest in establishing proper recycling processes to reduce the quantity of WEEE to be disposed of and to recover valuable resources.[46–48]

As shown in Fig. 3, Korea has two separate WEEE recycling systems: e-waste recycling centers run by producers and e-waste recycling facilities run by private operators. The producer recycling centers (e.g., Yongin recycling center, Asan Samsung recycling center, Chilseo LG recycling center, and Honam recycling center) are managed by either Korea AEE or major electronics manufacturers. Such recycling centers mainly process large home appliances such as refrigerators, air conditioners, and washing machines (Fig. 3). The private recycling facilities around the country recycle smaller amounts of WEEE than the producers do, and often deal with televisions, mobile phones, computers, and other consumer electronic equipment. Recycling of these devices, however, is not well established, and accurate information on the recycling quantities and the procedures followed is largely unavailable.

Figure 4 shows the processes used to recover valuable materials (e.g., ferrous metals, copper, and aluminum) from WEEE at one of the producers' electronic waste recycling centers in Korea. The procedures typically include manual dismantling, size reduction, magnetic separation, eddy current separation, and cyclone separation. In the practice of recycling WEEE, as a first step, it is very common to manually dismantle obsolete consumer devices to recover highly valuable materials and to remove toxic materials. Since the composition of WEEE is diverse and complex in terms of components and materials, it is very important to identify both valuable materials and toxic substances. For example, cables, circuit boards, refrigerants, oils, and compressors from refrigerators are manually removed in order to maximize the subsequent recovery of resources. A major concern of the current WEEE recycling process via dismantling, sorting, and other recovery processes is associated with uncontrolled emission of toxic chemicals (e.g., lead and polybrominated diphenyl ethers) to the surrounding environment.[8,18] There are also potential health hazards from fumes, dusts, and harmful chemicals affecting the recycling workers who process the components. Information regarding the emission of air pollutants at WEEE recycling facilities in Korea is not currently available.

In Korea, the recycling of WEEE is still in its early stages in terms of recycling technology and infrastructure. Due to the high cost of WEEE transportation and recycling, as well as a lack of consumer incentives for collection, only a small fraction of WEEE is being recovered and recycled. Therefore, many obsolete electronic devices are waiting for disposal from home storage. For example, it is estimated that more than 28 million used and end-of-life mobile phones were stored in households as of the end of 2006.[31]

Suggestions and conclusion

Waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams in Korea. The proper management of such equipment has become of major concern for solid waste professionals because of the large growth of the waste stream and the presence of a myriad of toxic materials within it. The generation of WEEE has been increasing in quantity and variety due to the wide use and replacement of electronic devices. In the past, WEEE was often mixed with household waste and treated in incineration facilities or disposed of in municipal solid waste landfills. In recent years, increased public concerns over the improper disposal of WEEE have led to a movement to regulate the waste more systematically and stringently by the Korea Ministry of Environment (Korea MOE). Over the past few years in Korea, a number of regulations and guidelines, such as extended producer responsibility (EPR), have been developed to better manage WEEE from consumers and to establish an integrated electronic waste management system. Since many of the measures initiated by the Korea MOE have only recently started, their outcomes may still be difficult to evaluate. However, several suggestions can be made to improve current WEEE management practices in Korea.

First, public recognition of the need for WEEE collection and recycling should be greatly promoted. A major challenge for WEEE collection is related to a lack of consumer awareness of potential hazards that result from improper disposal of WEEE. Consumer awareness of appropriate handling, source separation, and disposal of WEEE should be a priority in municipalities; it is essential that consumers should recognize the potential impacts of WEEE on human health and the environment, if improperly managed. Waste minimization through source reduction, reuse, and recycling also has to be effectively implemented to decrease the amount of WEEE to be disposed of. Waste minimization can be achieved by the following strategies: (1) encouraging consumers to purchase reusable electronic devices whenever possible (2) establishing effective policy for promoting the WEEE reuse market and recycling in collaboration with electronic waste recyclers.

Furthermore, one of the major challenges for WEEE recycling is the need to establish a proper collection system for a stable supply of electronic equipment to be recycled. It will be necessary to have continuous and stable demand for the recycled materials to establish the WEEE recycling industry. Especially, programs for WEEE collection by local governments have not been successful at promoting material recovery and recycling. They need to play a significant role in WEEE collection in municipalities by raising public awareness of the potential hazards of WEEE and the importance of WEEE recycling. Local governments should provide a place (municipal transfer facility) within the municipality where transporters contracted by the government can hand in consumer electronics to the recycling centers. Producers or importers should take discarded electronic products that have been collected by retailers and local governments and should transfer those products to recycling facilities for environmentally sound management.

More efforts have to be made to promote reuse and recycling of WEEE prior to final disposal, including economic incentive for collectors and development of recycling technology for various electronic devices. Recycling options should become a major part of WEEE management in Korea because incineration and landfilling are not currently accepted. Reuse and recycling of electronic equipment conserves energy and the precious materials contained in the equipment and reduces the environmental impact of these products upon disposal.

In recycling of WEEE, much work to date has focused on the recycling and recovery of materials from limited WEEE categories, especially refrigerators, washing machines, televisions, and air conditioners. According to the results obtained from this study, only small proportions of electronic devices covered by the EPR system are currently recycled. Thus, the EPR program needs to increase the target recycling rates to create an incentive to remove WEEE from storage. The recycling rates of other products such as computers, printers, and audio equipment are found to be even lower than those for the device categories mentioned above. This results partly from the lack of a sound and solid foundation for developing recovery and recycling techniques of the products. Thus, more efforts should be made to develop cost-effective recycling technologies. Since WEEE recycling can result in one of the greatest economic profits in the recycling industry, it would be valuable to study the potential and the dynamics of the WEEE recycling market.

Finally, categories and items in the EPR list, as promulgated by Korea MOE, need to be expanded to include small home appliances (e.g., vacuum cleaners and coffee makers) and other IT products (e.g., MP3 players and game players). Unlike the European WEEE system, current policy and regulation in Korea have focused on large home appliances and limited IT products (e.g., computers, printers, and mobile phones), as regulated by the WEEE Act. Thus, very limited information and official data with regard to generation, electronic waste flow, and recycling of many other electrical and electronic devices are currently available. As some of the aforementioned emerging issues and problems associated with WEEE management become better understood, the findings could provide a basis for better environmentally sound WEEE management in Korea.

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References

1. Korean Statistical Information Service (KOSIS) (2009) http://www.kosis.kr (accessed March 27, 2010)
2. International Telecommunication Union (ITU) (2008) http://www.itu.int/itd-d/jcteye/indicators/indicators.aspx# (accessed Aug 10, 2009)
3. Korea Communications Commission (KCC) (2008) The number of mobile phone subscribers: annual report (in Korean). The Commission, Seoul
4. Hilty L (2005) Electronic waste – an emerging risk? Environ Impact Assess Rev 25:431–435
5. Fishbein B (2002) Waste in the wireless world: the challenge of cell phones. Inform, New York
6. EnvirosRIS (2001) Options for recovery of end-of life IT equipment waste in Canada: final report submitted to Information Technology Association of Canada. Toronto
7. Jang Y, Townsend T (2003) Leaching of lead from computer printed wire boards and cathode ray tubes by municipal solid waste landfill leachates. Environ Sci Techol 37:4778–4784
8. Wang D, Cai Z, Jiang G, Leung A, Wong M, Wong W (2005) Determination of polybrominated diphenyl ethers in soil and sediment from an electronic waste recycling facility. Chemosphere 60:810–816
9. Vann K, Musson S, Townsend T (2006) Factors affecting TCLP lead leachability from computer CPUs. Waste Manag 26:293–298
10. Babu B, Parande A, Basha C (2007) Electrical and electronic waste: a global environmental problem. Waste Manag 27:307–318
11. Huo X, Peng L, Xu X, Zheng L, Qiu B, Qi Z, Zhang B, Han D, Piao X (2007) Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environ Health Perspect 25(5):1113–1117
12. Li H, Yu L, Sheng G, Fu J, Peng P (2007) Severe PCDD/F and PBDD/F pollution in air around an electronic waste dismantling area in China. Environ Sci Technol 41(16):5641–5649
13. Wong M, Wu S, Deng W, Yu X, Luo Q, Leung A, Wong C, Leung A, Wong C, Lukseburg W, Wong A (2007) Export of toxic chemicals – A review of the case of uncontrolled electronic-waste recycling. Environ Pollut 149:131–140
14. Five Winds International (FWI) (2001) Toxic and hazardous materials in electronics. Prepared for Environmental Canada, National Office of Pollution Prevention and Industry Canada, Computers for Schools Program, Quebec
15. Electronic Industry Alliance (EIA) (2000) The evaluation of materials used in personal computers. Prepared for the OECD, Arlington, VA
16. Minnesota Office of Environmental Assistance (MOEA) (2006) Minnesota Pollution Control Agency (MPCA) http://www.pca.state.mn.us/indexphp/waste/waste-home.html (accessed March 27, 2010)
17. California Department of Toxic Substances Control (CDTSC) (2006) Potentially toxic household items no longer allowed in trash bins of California homes or businesses. Available at: http://www.calepa.ca.gov/pressroom/Releases/2006/PR7-020906.pdf
18. Sjödin A, Carlsson H, Thuresson K, Sjölin S, Bergman Å, Östman C (2001) Flame retardants in indoor air at an electronic recycling plant and at other work environments. Environ Sci Technol 35:448–454
19. Townsend T, Jang Y, Ko J, Pearson B, Spalvins E, Wadanambi L (2003) Assessment of true impacts of e-waste disposal in Florida. Prepared for the Florida Center for Solid and Hazardous Waste Management. Report No 04-0232008, Gainesville, FL
20. Scharnhorst W, Ludwig C, Wochele J, Jolliet O (2007) Heavy metal partitioning from electronic scrap during thermal end-of-life treatment. Sci Total Environ 373:576–584
21. Marco I, Caballero B, Chomón M, Laresgoiti M, Torres A, Fernández G, Arnaiz S (2008) Pyrolysis of electrical and electronic wastes. J Anal Appl Pyrolysis 82:179–183
22. Spalvins E, Dubey B, Townsend T (2008) Impact of electronic waste disposal on lead concentrations in landfill leachate. Environ Sci Technol 42(19):7452–7458
23. Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, Schnellmann M, Boni H (2005) Global perspectives on e-waste. Environ Impact Assess Rev 25:436–458
24. He W, Li G, Ma X, Wang H, Huang J, Xu M, Huang C (2006) WEEE recovery strategies and the WEEE treatment status in China. J Hazard Mat B136:501–512
25. Liu X, Tanaka M, Matsui Y (2006) Electrical and electronic waste management in China: progress and the barriers to overcome. Waste Manag Res 24:92–101
26. Musson S, Vann K, Jang Y, Mutha S, Jordan A, Pearson B, Townsend T (2006) RCRA toxicity characterization of discarded electronic devices. Environ Sci Technol 40:2721–2726
27. Yang J, Lu B, Xu C (2008) WEEE flow and mitigating measures in China. Waste Manag B136:501–512
28. Kahhat R, Kim J, Xu M, Allenby B, Williams E, Zhang P (2008) Exploring e-waste management systems in the United States. Resour Conserv Recycl 53:955–64
29. Lee J, Song, H, Yoo J (2007) Present status of the recycling of waste electrical and electronic equipment in Korea. Resour Conserv Recycl 50:380–97
30. Min D (2006) National survey of discarded e-waste. Final Report submitted to Korean Association of Electronics Environment, Yongin
31. Jang Y, Lim S (2007) National survey of e-waste material flow analysis. Final Report submitted to Korean Association of Electronics Environment, Yongin
32. Jang Y, Kang H, Yoon H, Kim M, Kim Y (2008) Collection system and management practices of used and end-of-life mobile phones (in Korean). Korean J Waste Manag 25(1):82–89
33. EU Directive (2002) /96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE) – joint declaration of the European Parliament, the Council and the Commission relating to article 9. Official Journal L037:0024–0039
34. Aizawa H, Yoshida H, Sakai S (2008) Current results and future perspective for Japanese recycling of home appliances. Resour Conserv Recycl 52:1339–1410
35. Korea Ministry of Environment (Korea MOE) (2007) The Act on the Resource Recycling of Waste Electrical Electronic Equipment (WEEE) and End-of-life Vehicles (ELVs). The Ministry, Gwacheon
36. Japan Ministry of Economy, Trade and Industry (Japan METI) (2006) Report on the investigation of lifespan for four items of end-of-life home appliances (in Japanese). The Ministry, Tokyo
37. Yoshida A, Tasaki T, Terazono A, Moriguchi Y (2006) Material flow of used PCs in Japan. In: Proceedings of the third National Institute for Environmental Studies (NIES) workshop on e-waste. 2006, Nov. 17–18
38. United States Environmental Protection Agency (US EPA) (2007) Management of Electronic waste in the United States. http://www.epa.gov/ecycling/manage.htm
39. Silicon Valley Toxics Coalition (SVTC) (2002) Exporting harm: the high-tech trashing of Asia. The Basel Action Network, Seattle
40. International Association of Electronics Recyclers (IAER) (2006) International Association of Electronics Recyclers Industry Report. Available at http://www.iaer.org/commnications/indreports.htm

41. Korea Ministry of Environment (Korea MOE) (1991) The Act on the Promotion of Conservation and Recycling of Resources. The Ministry, Gwacheon
42. Korea Ministry of Environment (Korea MOE) (2002) The Act on the Promotion of Conservation and Recycling of Resources (Revised by Korea MOE). The Ministry, Gwacheon
43. EU Directive (2002) 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in waste electrical and electronic equipment (RoHS). Official Journal L037:0019–0023
44. EU Directive (2000) 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles (ELV). Official Journal L269:0034–0043
45. Korea Environmental and Resources Corporation (Korea ENVICO) (2009) http://www.envico.or.kr
46. Hischier R, Waeger P, Gauglhofer J (2005) Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environ Impact Assess Rev 25:525–539
47. Sinha-Khetriwal D, Kraeuchi P, Schwaninger M (2005) A comparison of electronic waste recycling in Switzerland and in India. Environ Impact Assess Rev 25:492–504
48. Cui J, Forssberg E (2007) Characterization of shredded television scrap and implications for material recovery. Waste Manag 25:415–424

Green IT awareness and practices: results from a field study on mobile phone related e-waste in Bangladesh

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Abstract

This paper presents preliminary findings from a 'Green IT' research project, dealing with mobile phone and battery disposal and recycling by businesses and individuals in Bangladesh. Electronic waste (e-waste) is one of the fastest growing sources of waste. In addition to facing the issue of illegal exports of toxic e-waste, containing heavy metals, from the developed to the developing world, waste from current and emerging technologies used in developing countries is also growing, with the rapid increase in the use of computers, mobile phones and other devices. While many of the major electronics firms have initiated clean up practices aimed at reducing the e-waste problem, e.g. disposal and re-cycling initiatives, such schemes have in general not reached developing nations. The increasing e-waste has environmental, health, and other social implications in many developing countries, particularly with only a low level of awareness of this issue, as is the case in Bangladesh. The research presented in this paper, carried out in October-November 2009, covered awareness, current and planned practices of Green IT among 15 interviewees in Bangladesh, with special focus on mobile phones and batteries. Following an overview of Green IT in general and e-waste in particular, the paper outlines the methodology of the study, research findings and policy recommendations arising from the research results.

1. Introduction

As the reach of ICT expands into the developing world, so does its impact on the environment, both positive and negative. Opportunities associated with ICT and the environment include transport and travel substitution, using IT to deal with issues like enforcement and promotion of environmentally friendly practices, and in appliances that can advance sustainability through reduced energy consumption [1, 2]. A key finding in a major study on ICT and sustainability was that several ICT applications cancel each other out, leading to the conclusion that a set of specific ICT-related policies is necessary to harness the potential of ICT to support sustainable development, while at the same time inhibit its potential for negative environmental impacts [3]. Several studies on the environmental impact of e-commerce have also been inconclusive with respect to environmental impacts [4, 5].

The challenges and opportunities are both included in what is often referred to as "Green IT" [6], a concept increasingly embraced, primarily in developed countries, as a topic of research, promotion, and practice. However, academic communities and others in the developing world have been slow to acknowledge the issues and take action to promote Green IT.

Green IT addresses environmental impacts of the whole IT life-cycle, ranging from designing an IT device, to its use and its end-of-life management [7]. Highlighting issues such as CO_2 emissions, the concept emphasizes the need to adopt practices that will lead to less energy

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consumption and IT-waste, whether dealing with small devices such as mobile phones or large energy intensive data centers.

One of the major concerns of Green IT is the alarming increase in global IT-waste. With ever changing new models of almost every IT device, businesses and consumers frequently upgrade to newer models, thereby contributing to IT waste. Green IT is also concerned with the operational level of IT, i.e. who should be responsible for proper Green IT practices.

The objective of this paper is to explore awareness levels and attitudes towards disposal of mobile handsets and their batteries in Bangladesh, in the context of Green IT. The reason for focusing on mobiles is that these are the most prevalent form of ICT in Bangladesh. The paper reports on preliminary research aimed at answering the following research questions:

- What are the practices regarding disposal and recycling of mobile phone handsets and batteries among IT professionals and other users in Bangladesh and what is the awareness level of Green IT practices ?

- What are the future plans regarding these issues and what actions could be suggested for a better disposal system for mobile handsets and batteries?

We start this paper with a summary of the Green IT concept. Following an overview of the research methodology, we present preliminary research results and conclude with suggestions for future directions.

2. Concept of Green IT

From the business point of view, *"Green IT is part of a fundamental change in the economy and society. It is a subset of the larger green (sustainable) business trend, which reconciles sustainable business practices with profitable business operations"* [8].

Green IT is thus also concerned: "*about energy consumption and subsequent carbon dioxide emissions from commercial ICT equipment*" [9]. With the estimated global power use for servers having doubled between 2000 and 2005, and with predictions of an increase in the order of 40% by 2010 [10], the growing data centre sector is looking for greener options: "*Going green in the data centre have many facets such as reducing overall power consumption, maximizing power utilization, reducing the amount of hardware via consolidation, and decreasing the amount of storage required to meet data processing requirements*" [11].

As Green IT is a broad concept, endeavouring to meet the needs of present generations without compromising the ability of future generations to meet their needs, it involves pollution prevention at the beginning and end of a product's life-cycle, product stewardship to minimize the environmental footprint during use, adoption of clean technologies to reduce pollution, and development of environmentally friendly competencies [12].

Elliot identified four phases of Green IT, defining them as: *"the design, production, operation, and disposal of ICT and ICT-enabled products and services in a manner that is not harmful and may be positively beneficial to the environment during the course of its whole-of-life* [13]*"*

The following definition is another summary of Green IT, incorporating eco-sustainability, IT-infrastructure, and supply chain in a green perspective: *"Green IT is an organization's ability to systematically apply environmental sustainability criteria (such as pollution prevention, product stewardship, use of clean technologies) to the design, production, sourcing, use and disposal of the IT technical infrastructure as well as within the human and managerial components of the IT infrastructure"*. [6].

Info~Tech [14] defined the various elements of Green IT as "*equipment recycling, server consolidation and virtualization, optimizing data centre energy efficiency, print optimization, data centre airflow management, rightsizing IT equipment, green considerations in sourcing and RFPs, hot aisle/cool aisle data centre layout, budget allocation for Green IT projects, liquid cooling for IT equipment, DC powered IT equipment, airside/waterside economizer, carbon offsetting*".

The above definitions of Green IT, whether from the commercial or academic sectors, clearly point to e-waste as an integral element of this concept. This matters from a policy perspective, as it will facilitate the inclusion of e-waste in policies dealing with Green IT at a time when the emphasis is more likely to be on energy consumption.

2.1. Green IT practice in developed nations

Developed countries are taking the Green IT issue seriously, incorporating aspects such as energy-efficiency, reduction of carbon-dioxide emissions and proper IT-waste management. South Korea is very close to becoming the world leader in green technology, as organizations are adopting a wide array of government policies supporting green technologies. Having shown strong leadership and committed substantial public funding for "green" technologies, the South Korean government is working to institute stronger certification requirements for manufacturers who want to use a "green" label on their IT devices, similar to Energy Star in the United States [15].

According to the IDC-Dell Green IT Barometer, almost half of European enterprises are addressing the green and sustainable challenges facing them, with 35% of the respondents reporting that they had a Green IT strategy, while a further 16% had plans to implement such a strategy within the next 24 months [16].

There is industry support in Japan for the government's large scale promotion of Green IT, with the Japan Electronics and Information Technology Industries Association having established the Green IT Promotion Council in 2008 and moving quickly to exchange an MOU with concerned groups in the US in 2009. Japan has also started working with the US and the EU to establish new standards for datacenters [17].

A number of national, professional and inter-governmental institutions are developing guidelines related to green ICTs. Examples include: The Commonwealth of Australia Green Office Guide [18]and the US Environmental Protection Agency's initiative to study energy use in data centers [9]. Most Green IT policies address e-waste. In the US, 18 states have mandated e-waste recycling, and in all of them except California, manufacturers are required to pay for such recycling [19]. According to estimates by the United Nations, some 20 to 50 million tons of e-waste are generated each year [20], constituting 70% of all hazardous waste, much of which is bulky and complicated to recycle. The US Environmental Protection Agency estimated that over 25 billion computers, televisions, cell-phones, printers, gaming systems, and other devices sold since 1980, generated around 2 million tons of electronic waste in 2005 alone, with only 15-20% being recycled [19]. Research completed in Europe shows that electronic waste is growing at three times the rate of other municipal waste [21]. E-waste in Australia is estimated to grow at more than three times the rate of general municipal waste [22]. A comparative study among organizations in the US, New Zealand and Australia found that 80% of respondents considered e-waste management and IT's energy consumption the two main environmental concerns among respondents [7].

2.2. The problem of e-waste and its impact on developing countries

Many developing nations, including Bangladesh, are expected to suffer most from the climate change, a problem to which they did not contribute much.

The concern is so high that the State Minister for Environment and Forest, Dr Hasan Mahmud demanded 5.0 billion US dollars from the developed countries in compensation for climate change impacts during a meeting of the United Nations on environment affairs. As Dr. Mahmud expressed it: "Bangladesh is not responsible anyway for the worldwide environmental problems, whereas it is in the most vulnerable position as a nation at risk" [23].Unlike developed nations, there is still considerable lack of knowledge in Bangladesh of the damage caused to their environment by non Green IT practices.

One case in point is e-waste, which is one of the fastest growing sources of waste.

Much of the e-waste collected in the developed world is exported, often illegally, to sub-standard treatment plants in developing nations [24], e.g. the US ships up to 80 percent of its e-waste to China. Canada, Japan, and South Korea also send much of their e-waste to Guiyu, China [20], where e-waste recycling is big business, with the consequence that 82% of children under the age of six suffer from lead poisoning. A similar problem is playing itself out in Africa. In the Ikeja Computer Village, near Lagos, Nigeria, thousands of vendors are packed into the market, where all kinds of electronics can be purchased. Up for sale are computers, fax machines, cellular telephones, and other devices that have been repaired [25]. Although Nigeria has a good repair market, it lacks a system to safely deal with e-waste. Most of it is disposed of in landfills and unofficial dumps [25].

Developing countries also generate significant e-waste, e. g. India generates between 146,000 - 330,000 tons a year, growing at a rate of 34% a year [26]. So it is very important to raise awareness and concern in developing countries about imported as well and internally generated e-waste in developing countries

2.3. Disposal of mobile batteries and handsets

It is estimated that in the United States 130 million mobile phones had been discarded by 2005, resulting in 65,000 tons of e-waste [27]. With an estimated 21 million mobile phones in Australia, about one for every person, and an average of 12-24 months lifetime, there is a high replacement rate [28].

Globally, more than 2.17 billion people currently use mobile phones, and this number is growing [29]. Each year, 130 million mobile phones are retired [21].

Mobile phones contain a cocktail of highly toxic elements, such as cadmium, arsenic and lead [30], posing very serious global pollution concerns both from the standpoint of disposal and recycling, whether disposed of where the phones were used or through transboundary movements of such waste [31].

According a University of Florida Study, the average composition of mobile phones (excluding batteries) tested contained 45% plastics, 40% printed wiring (or circuit) board, 4% liquid crystal display (LCD), 3% magnesium plate, and 8% metals [31].

Mobile phone batteries also contain high levels of toxic elements, such as cadmium and brominated flame-retardants [301. Virtually all batteries contain material that will result in hazardous waste unless disposed of appropriately, including rechargeable nickel-cadmium batteries, silver button batteries, mercury batteries, small sealed lead-acid batteries, and alkaline batteries [32]. The environmental impact of mobile phones and batteries depends on their material composition and the length of time they have been in use when discarded. Many mobile phone users replace their batteries at least once before retiring their phones [31].

2.4. Green IT in Bangladesh

The prime concern of the many environmental organizations active in Bangladesh is related to the preservation of threatened species and native forests. There is little evidence that these organizations are doing anything about waste management in general or e-waste in particular. One of the leading environmental groups in Bangladesh, Bangladesh Environmental Lawyers Association (BELA), is currently working with the campaign against the hazardous and unsafe scrap shipyard in Chittagong [33]. More recently, there have been signs of growing government interest in Green IT issues, as evidenced in a proposed new national ICT policy, formulated by a government nominated review committee in 2008. Recommendations in the report include promotion of environmental preservation by adopting environment-friendly green technologies and of environmental protection through the use of ICT tools. Encouragingly, and of considerable relevance to this study, the report also recommended the safe disposal of toxic wastes resulting from use of ICTs. Environmental objectives would be achieved through actions like mandating energy saving and low power consumption ICT devices, setting and enforcing regulatory standards to control dumping of ICT devices, reducing use of paper, adopting effective resource management, using ICT to create awareness in different areas like agriculture, sanitation, water management [34].

But neither BELA, nor the government of Bangladesh have taken publicly visible initiatives to raise awareness of the e-waste generated in Bangladesh. In a time of digitization, with increasing amounts of e-waste, there also does not seem to be much concern among users of ICT devices about the implication of dumping e-waste in landfills.

This preliminary research explored awareness and practices with respect to e-waste among the interviewees and sought their views on what would be required to make them change practices that are not consistent with the Green IT perspective.

3. Research Methodology

The nature of this research is explorative, focussing on complex social actions in order to understand awareness levels of Green IT practices, particularly those relating to disposal and recycling of mobile phone handsets and associated batteries among IT professionals, employees of mobile phone repair shops, and general mobile phone users in Bangladesh. Lack of previous studies and data in this area also suggests the use of qualitative research to be the most appropriate methodology to identify issues for a possible future quantitative study.

Table 1. Profile of interview participants

Category of participants	Number	Topic of the interview
IT professionals	3 1 female 2 male	• Awareness level of Green IT, • Interests in adoption of Green IT practices, • Mobile handset usage pattern, • Disposal of mobile batteries, • Role of their companies, towards better disposal system of mobile batteries, • Proposed solution for the disposal problem of mobile batteries.
Mobile phone repair shops	2 male	• Suggestions for the disposal of mobile batteries , • Number of handsets sold per month, • Any guidance provided to customers for the safe disposal of mobile handsets.
General users	10 5 male 5 female	• Interest in adoption of Green IT practices, • How they dispose of their mobile handsets and batteries, • Intention towards adoption of safe disposal practices, • Mobile handset usage patterns.

A purposive selection procedure was applied to identify 15 interviewees, the maximum number we could cover, considering time and resources available for this study. Organizations in the ICT sector and repair shops were selected on the basis of how long they had been in operation in Bangladesh, market share, business size, to get some diversity among this small number of interviewees. Furthermore, the repair shops were chosen on the basis of our understanding of their popularity and longevity, with some having been in operation for more than ten years in the central business district. The idea was to seek information from persons who interact most with a diverse range of customers. We expected the repair shops to be knowledgeable about how their customers think about mobile phones and batteries and to play a role in the handling old handsets and batteries. IT professionals and respondents from mobile phone repair shops were selected on the basis of number of years of employment, relevant areas of employment, and access to organization policy. One of the IT professionals had worked in the company for nine years, was head of the IT department, and holds bachelor and master degrees in management information systems. He was selected because of his familiarity with the company's policies and practices. The in-depth interview was about his views and Green IT related practices of the company. The organization is one of the major telecommunication companies in Bangladesh, so we could get a reasonable picture from the interview about the "Green IT" awareness and practices in a top-tier organization. Another IT professional was a female engineer working with a leading telecommunications service provider as head of operations and maintenance. She had been working in this company for 5 years, and had 4-5 years previous experience from two IT companies prior to commencing with her current employer. The third IT professional had recently completed his degree in computer science and worked in a Bangladesh-Canadian partnership firm. The reason for including hi is that he could contribute with a perspective from the younger generation in the workforce, particularly new IT graduates who are likely to start influencing Green IT policies and practices in public and private organizations in the near future.

The general users, were selected randomly among students from the University of Dhaka

The researcher acted as a mediator of in-depth interviews. There were a few predefined questions, centering on the current awareness level of Green IT practices, with particular emphasis on the disposal and recycling of ICT related components (see Table 1 for details).

Interviews were voice-recorded in the local language of Bengali. All interviews were transcribed in Bengali and then translated into English by the researcher. To improve accuracy, the interviews were also translated by someone outside the research group. A thematic data analysis technique was deployed to identify various themes from the field data.

4. Preliminary Field Survey

4.1. Green IT knowledge and awareness

The term Green IT was very unfamiliar to interviewees in the general user category. Though they sensed that the concept would have to be related to the environment as the word "Green" has environmental connotations, they were not aware of the relationship between Green IT and the disposal of mobile handsets and batteries. A common finding among general users was that they had not heard of the term "Green IT" before the interviews. One respondent commented, "*We are not aware because there isn't any awareness building programs or information out there. There are other environmental issues, we have heard of, but environmental issues related to disposal of mobile handsets and batteries are rarely discussed*". IT professionals though, showed great concern and awareness about e-waste and environmental issues, but they were not familiar with the term "Green IT". One respondent, who is the head of the IT department, explained that his employer is promoting greener practices at the workplace, but the term Green IT was still unknown. Another IT professional, who works with firms across the globe, was however well aware of the term Green IT, stating: "*Our international customers are trying to do business in the Green IT way, still it's hard to deploy Green IT practices in Bangladesh as there is not much awareness. The business owners are not at all interested in such ideas.*" With respect to the repair shops, we found that employees in these were not at all aware of the dangers of disposing of mobile phones in the garbage, let alone the concept of Green IT.

4.2. Intentions towards Green IT policies / Readiness to adopt Green IT

Although most respondents were unfamiliar with the term Green IT, some of them were aware of key issues associated with the concept, without being familiar with the term. The general mobile phone users showed much interest in the preservation of the environment and practices that help achieving this. "*It's a shame, we are not much aware of the hazards that we can cause by doing things the wrong way. Proper disposal of anything is necessary. We just ruin out environment and later cry for it*". Another respondent went further, *"we all talk about the environment and saving it, but we all throw rubbish on the road. The least we could do is to stop throwing garbage everywhere. People have to understand very clearly how dangerous it is to throw IT waste away in the dumps, before that they won't care"*. Though the respondents were positive about contributing to Green IT, convenience of its practices also emerged as an important issue, as a respondent said, "*I will continue to support and adopt Green IT practices as long as it is not creating any inconvenience in my life.*"

4.3. Mobile device practices

More than half of the respondents had more than one mobile phone for various reasons, e.g. for battery back-up purposes and keeping different numbers for personal and professional matters. When respondents faced problems with reduced talk time, sometimes they changed the whole phone, and in other cases changed the batteries only, or kept an extra set for back-up. Some of them threw away old phones. Most of the respondents believed they had changed at least 4-5 mobile handsets during the past 10 years. One user answered he had used 13 mobile handsets since 2003, five of which were stolen and hijacked, and the rest sold after some time. Once, when there was a battery problem, he replaced the old battery with a new one and left the old battery at the repair shop. Another respondent in the same scenario, kept his old battery and said, *"I don't know why I kept the battery to myself, I just did. I didn't throw it away. I didn't feel like throwing it away*". Some of the respondents had at least one non-operating handset somewhere in their home. The majority of the respondents said they gave their old mobile phone away to someone needy who could repair and reuse it. One problem with this type of "give-away" is that the sets could be transferred to less literate people, who may be less careful about waste related issues.

But almost all the respondent had dumped at least one handset or a battery in the dustbin. One of the IT professionals threw his handsets away in earlier times of mobile usage and said, *" I did throw my cell phone away, but then the scenario was different. There was little chance to repair a handset for the lack of such facilities in the market. But now, I probably won't throw my cell phone away. I will try to repair and reuse it and that would be good for the environment also."*

4.4. Treatment of IT waste (especially mobile handsets and batteries)

E-waste, especially mobile handsets and batteries are treated less seriously as hazardous waste than lead-acid batteries used in cars and for power supply back-up. Battery suppliers are legally obliged to accept such batteries from their customers, who have adopted the practice of returning old batteries to their supplier. One of the respondents pointed out this fact and said, *"If the mobile sellers or operators made it mandatory to do the same with the mobile batteries, the scenario might change."* Some other respondents supported this by saying, "*people are motivated by big names. I will definitely respond if the campaign is run by any big names or there is any big brand related to it."*

This is consistent with the finding that firms, when deciding to adopt environmental practices, are influenced by social and institutional considerations [35].

IT professionals were quite aware of the environmental implications of throwing away handsets and batteries and considered that toxic waste like e-waste should be prevented from being disposed of in landfills, as a matter of urgency. Simple procedures, like using colored bags or bins for different types of garbage, should in their view be adopted as part of waste management practices, with special attention to IT waste. One of the IT professionals interviewed argued, "*People are more aware and concerned about the environment than ever before. Maybe it's because of the green house effect and climate change, that are going to affect them directly, but this has led to a situation where issues related to environment are taken seriously. So, if awareness is raised, people are going to respond in a positive way."*

4.5. Pollution prevention

It was interesting to note that all respondents had something to say or suggest about protecting the environment and preventing pollution. One respondent was very particular and sensitive about the environment issue, firmly believing that pollution should be stopped. To prevent mobile handsets and batteries from ending up in landfills, she suggested "point of sale" advertisements, considering this would definitely reach the target market. She also thought awareness could be raised with messages printed on the packaging in which mobile handsets are sold. Another interesting comment from a general user was: *"Seminars and workshops are boring and they don't reach the mass people. The message could be spread using electronic and print media and it should be designed to capture the attention of the audience and touch them emotionally"*. Another idea was for the government to impose strict rules. In summary, if the pollution and e-waste problems are dealt with carefully, participants were positive about them being solved.

4.6. Green IT commitment and governance among organizations

One IT professional indicated that the company he worked for was already taking initiatives to make it greener, by adopting practices such as double-sided printing and eliminating unnecessary printing. One method of discouraging printing, considered by the company, was to introduce a system whereby employees would have to use their IDs to print anything. Another organization had introduced a "Go Green" campaign, encouraging employees to switch off power when not required, e.g. lights, and placing their PCs in standby or sleep mode. The company set a target of how much power to save within a specified period, and when the actual savings exceeded the target, employees were given bonuses related to the amount of power saved. This was a definite motivation for them; doing something good and being rewarded for it.

One problem that is difficult to solve at the organizational level relates to hardware obsolescence, as pointed out by one respondent: *"The upgraded versions of recent software have created the problem of constant hardware upgrades. So the companies have to upgrade to newer PCs even if the old ones are perfectly in shape. Upgrading old computers to reuse can be an option."*

5. Summary, limitations and future research direction

Figure 1 illustrates the key findings of this study, identifying the present situation and a possible future scenario of Green IT (e-waste disposal and recycling) in Bangladesh. In the current situation, there is considerable lack of awareness, which has led to unregulated increase in the e-waste volume. Without recycling and/or proper disposal facilities, this e-waste is creating hazardous environments, the consequences of which have been widely addressed in previous research. The government of Bangladesh could prevent such consequences by imposing strict regulations, with severe penalties for those disposing of e-waste, whether locally produced or imported, and by conducting awareness

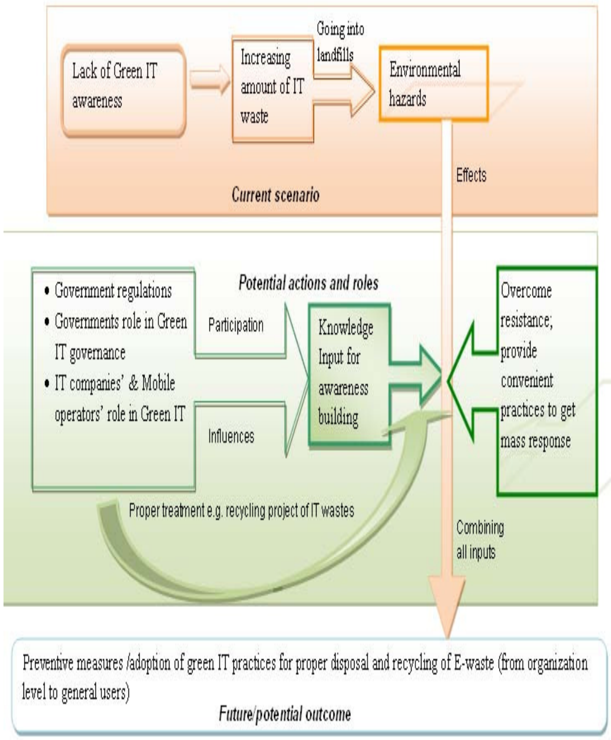

Figure 1 An Overview of Green IT (mobile battery disposal) situation in Bangladesh

campaigns. Whether the government acts or not, mobile operators could also raise the level of awareness. Even if the government does not introduce a mandatory recycling scheme, companies could start doing this as a part their corporate social responsibility. The key ingredient towards adoption of Green IT practices and changing the attitude of the public towards Green IT is to create awareness of this issue. Most of the participants in the study agreed that a high level of awareness is needed for effective e-waste management. Another obstacle to overcome is that people expect convenience when dealing with environmental issues. It would be necessary for this to be taken into account when designing new measures in order to maximize the probability of these measures being successful. A mix of strong regulations, corporate initiatives in this area, awareness raising, and convenience would, according to the interviewees be effective in achieving proper disposal and recycling of e-waste by organizations and general users.

A major limitation of this study is the small sample and its unrepresentative nature. All respondents were reasonably privileged, living in Dhaka. It would be important to expand the research to incorporate representatives from all sectors of the Bangladeshi society who are likely to use mobile phones, including users outside the capital city. With more than 70% of the population living in rural areas, it would be important to incorporate their views, particularly with the increasing mobile phone use in those areas. As was the case for the urban respondents, the concept of Green IT is likely to be unfamiliar to respondents in rural areas and, much time would be required explaining and clarifying this concept and associated questions.

Another limitation is the lack of relevant data, as Green IT is an emerging topic in Bangladesh, and there is not much research in this field. This, in combination with many aspects of Green IT, still to be explored, presents challenges and opportunities for researchers. In addition to a more representative study on mobile phone and battery disposal, it would be useful to expand the research to include personal computer related waste in Bangladesh. Government policies and programs related to Green IT in Bangladesh are other research areas that would contribute to knowledge in this critical area. With the government working on a new ICT policy, this would be a good time to raise public awareness of e-waste, particularly in light of the rapid spread of ICT devices in the country. The insights reported in this paper could provide useful input from a user perspective into the policy development process and associated implementation practices.

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References

[1] R. Watson, M. Boudreau, and A. Chen, "Information Systems and Environmentally Sustainable Development: Energy Informatics and New Directions for the IS Community," *MIS Quarterly*, vol. 34, no. 1, pp. 23-38, March 2009.

[2] J. Houghton. "ICTs and the Environment in Developing Countries: Opportunities and Developments". In *The Development Dimensions, ICTs for Development. Improving Policy Coherence*, OECD, 2009, pp. 149-175.

[3] L. Hilty, P. Arnfalk, L. Erdmann, J. Goodman, M. Lehmann, and P. Wäger, "The Relevance of Information and Communication Technologies for Environmental Sustainability

– A Prospective Simulation Study," *Environmental Modelling and Software,* vol. 21, no. 11, pp. 1618-1629, Nov. 2006.

[4] M. M. Velásquez, A. Ahmad, and M. Bliemel, "State-of-the-Art in E-Commerce Carbon Footprinting, Journal of Internet Banking and Commerce," *Journal of Internet Banking and Commerce, vol. 14, no. 3, Dec. 2009. [Online]. Available:* http://www.arraydev.com/commerce/JIBC/2009-08/SI_Marcelo.pdf. [Accessed: March 19, 2009].

[5] L. Yi, and H.R. Thomas, "A Review on the Environmental Impact of e-business and ICT," *Environmental International,* vol. 33, no. 6, pp. 841-849, Aug. 2007.

[6] A. Molla, V.A. Cooper, H. Deng, and S. Lukaitis, "A Preliminary Report on Green IT Attitude and Actions Among Australian IT Professionals," *School of Business Information* Technology, 2009. [Online]. Available: http://greenit.bf.rmit.edu.au/index.php/working-papers.html. [Accessed: Oct. 5, 2009]

[7] A. Molla, S. Pittaychawan, and B. Corbitt, "Green IT Diffusion: An International Comparison," *School of Business Information Technology,* 2009, [Online]. Available: http://greenit.bf.rmit.edu.au/Working_Paper/GITWP1_2009.pdf. [Accessed: Oct. 2, 2009].

[8] C. Mines, and E. Davis, "Topic Overview: Green IT," *Forrester Research,* Nov. 26, 2007.[Online]. Available: http://www.forrester.com/Research/Document/Excerpt/0,7211,43494,00.html. [Accessed: Oct. 10, 2009].

[9] ACS- Australian Computer Society, "Australian Computer Society Policy Statement on Green ICT," *ACS- Australian Computer Society*, 2007. [Online]. Available: http://www.acs.org.au. [Accessed: Oct. 10, 2009].

[10] J. Koomey, "Estimating total power consumption by servers in the U.S. and the world", Analytics Press, Oakland. http://enterprise.amd.com/Downloads/svrpwrusecompletefinal.pdf [Accesssed: Mar 22, 2010.

[11] Brocade, "Storage Area Network: Going Green with Brocade," *Brocade communications systems, Inc.*, 2007. [Online]. Available: http://www.greendatasystems.com. [Accessed: Oct. 12, 2009].

[12] S. L. Hart, "*Beyond greening: strategies for a sustainable world,*" *Harvard Business Review*, vol. 75, no. 1, pp. *66-76*, Jan. 1997.

[13] S. Elliot, "Environmentally Sustainable ICT: A Critical Topic for IS Research," in *Pacific Asia Conference on Information Systems,* 2007, pp. 99-112.

[14] Info~Tech, *11 Green Initiatives Your Peers are Cultivating*, Info~Tech Research Group, July 30, 2007.

[15] D. Castro, "Learning from the Korean Green IT Strategy," *The Information Technology & Innovation Foundation Web Memo,* 2009. [Online]. Available: http://www.greenbiz.com/research/report/2009/08/11/learning-korean-green-it-strategy. [Accessed: Oct. 4, 2009].

[16] N. Martinez, and K. Bahloul, "Green IT Barometer: European Organisations and the Business Imperatives of Deploying a Green and Sustainable IT Strategy," *International Data Corporation,* 2008. [Online]. Available: http://content.dell.com/us/en/corp/d/corporate~research~en/Documents~idcwp28q.pdf.aspx. [Accessed: Oct. 6, 2009].

[17] Green IT Promotion Council, "Green IT Initiative in Japan," *Green IT Promotion Council,* 2009. [Online]. Available: http://www.greenit-pc.jp/activity/asia/file/japan_rink.pdf. [Accessed Dec. 15, 2009].

[18] Commonwealth of Australia. "Green Office Guide", 2001.

[19] S. Ruth, "Green IT-More than a Three Percent Solution?," *IEEE Internet Computing,* vol. 13, no. 4, pp. 74-78, July 2009.

[20] T. Vetter, and H. Creech, "The ICT Sector and the Global Connectivity System: A sustainable development overview," *The International Institute for Sustainable Development, IISD, Winnipeg,* 2008. [Online]. Available: http://www.iisd.org/pdf/2008/ict_global_con_sd.pdf. [Accessed: Dec. 10, 2009].

[21] M. Poniatowski, *Foundations of Green IT: consolidation, virtualization, and ROI in the data center.* United States: Prentice Hall, 2009.

[22] Australia. Australian Bureau of Statistics. *Environment snapshot: recycling up, but e-waste a looming issue,* no. 4613.0, Canberra: Australian Bureau of Statistics, 2006.

[23] Thefinancialexpress-bd.com, "Dhaka Seeks $5 B as a Climate Change Compensation," *Thefinancialexpress-bd.com,* Sept. 25, 2009. [Online]. Available: http://www.thefinancialexpress-bd.com/search_index.php?page=detail_news&news_id=79773. [Accessed Oct. 21, 2009].

[24] European Union, "Questions and answers on the revised directive on waste electrical and electronic equipment (WEEE)," *European Union,* 2008. [Online]. Available: http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/08/764. [Accessed: Dec. 11, 2009].

[25] T. J. Velte, A. T. Velte, and R. Elsenpeter, *Green IT: Reduce Your Information System's Environmental Impact While Adding to Bottom Line.* New York: McGraw Hill Companies, 2008.

[26] V. N. Pinto, "E-waste hazard: The impending challenge," *journal of occupational and environmental medicine,* vol. 12, no. 2, pp. 65-70, May 2008.

[27] B. K. Fishbein, "*Waste in the Wireless World: The Challenge of Cell Phones,"* Inform, New York, 2002.

[28] Infoplease, “Cell Phone Usage Worldwide, by Country,” *Infoplease,* n.d.. [Online]. Available: http://www.infoplease.com/ipa/A0933605.html. [Accessed: Oct. 12, 2009].

[29] Australian Mobile Telecommunications Association, “Mobile Telecommunications Industry Statement of Commitment to Mobile Phone Recycling,” *Australian Mobile Telecommunications Association,* 2008. [Online]. Available: http://www.mobilemuster.com.au/files/GMobileMusterGovernmentNational.Public.StatementMPIRP.National.Statement.271108.pdf. [Accessed: Oct. 10, 2009].

[30] Clean Up Australia, “Mobile Phone Fact Sheet,” *Clean Up Australia,* 2009. [Online]. Available: http://www.cleanup.com.au. [Accessed: Oct. 2, 2009].

[31] Basel Action Network, “Mobile Toxic Waste: Recent Findings on the Toxicity of End-of-Life Cell Phones,” *Basel Action Network*, 2004. [Online]. Available: http://www.ban.org/Library/mobilephonetoxicityrep.pdf. [Accessed: Oct. 2, 2009]

[32] California State University, “Environmental Compliance,” *California State University,* 2005. [Online]. Available: http://daf.csulb.edu/offices/bhr/safetyrisk/envcomp.html. [Accessed: Oct. 3, 2009].

[33] World Watch Institute, “Bangladeshi Lawyer Fights Toxic Ship-Breaking,” *World Watch Institute,* 2009. [Online]. Available: http://www.worldwatch.org/node/6084. [Accessed: Oct. 4, 2009].

[34] Bangladesh. The Ministry of Science and Information & Communication Technology. *National ICT Policy*

[35] P. González, “Analysing the Factors Influencing Clean Technology Adoption: A Study of the Spanish Pulp and Paper Industry,” *Business Strategy and the Environment,* vol. 14, no. 1, pp. 20-37, Jan. 2005.

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Application of Delphi-AHP methods to select the priorities of WEEE for recycling in a waste management decision-making tool☆

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ABSTRACT

The management of waste electrical and electronic equipment (WEEE) or electronic waste (e-waste) has become a major issue of concern for solid waste communities due to the large volumes of waste being generated from the consumption of modern electrical and electronic products. In 2003, Korea introduced the extended producer responsibility (EPR) system to reduce the amount of electronic products to be disposed and to promote resource recovery from WEEE. The EPR currently regulates a total of 10 electrical and electronic products. This paper presents the results of the application of the Delphi method and analytical hierarchy process (AHP) modeling to the WEEE management tool in the policy-making process. Specifically, this paper focuses on the application of the Delphi-AHP technique to determine the WEEE priority to be included in the EPR system. Appropriate evaluation criteria were derived using the Delphi method to assess the potential selection and priority among electrical and electronic products that will be regulated by the EPR system. Quantitative weightings from the AHP model were calculated to identify the priorities of electrical and electronic products to be potentially regulated. After applying all the criteria using the AHP model, the results indicate that the top 10 target recycling products for the expansion of the WEEE list were found to be vacuum cleaners, electric fans, rice cookers, large freezers, microwave ovens, water purifiers, air purifiers, humidifiers, dryers, and telephones in order from the first to last. The proposed Delphi-AHP method can offer a more efficient means of selecting WEEE than subjective assessment methods that are often based on professional judgment or limited available data. By providing WEEE items to be regulated, the proposed Delphi-AHP method can eliminate uncertainty and subjective assessment and enable WEEE management policy-makers to identify the priority of potential WEEE. More generally, the work performed in this study is an example of how Delphi-AHP modeling can be used as a decision-making process tool in WEEE management.

1. Introduction

Once electrical and electronic products reach the end of their useful life, they become waste electrical and electronic equipment (WEEE), which is often referred to as electronic waste (or e-waste in short). WEEE streams encompass a wide range of electrical and electronic waste products, including home appliances (e.g., refrigerators, washing machines, air conditioners); information technology and telecommunication equipment (e.g., personal computers, notebook computers, printers, copying equipment, calculators, facsimiles, telephones, mobile phones); consumer electronic devices (e.g., televisions, radios, video cameras, audio equipment); and other household electrical and electronic equipment (e.g., vacuum cleaners, toasters, coffee machines, hair dryers, watches, irons). WEEE is one of the fastest growing solid waste streams in many countries (Babu et al., 2007). The generation of WEEE has increased in quantity and variety due to the wide use and common replacement of electronic devices in this modern technology-driven society. As the life cycles of electrical and electronic products are becoming shorter, the quantity of WEEE is expected to increase in solid waste streams. Thus, proper management of WEEE has become a major concern for solid waste professionals because of the large growth of the waste stream as well as the presence of myriad toxic materials within it (e.g., lead,

☆ Summary: This paper presents the application of the Delphi-AHP method to determine the priorities of waste electrical and electronic equipment (WEEE) for recycling through the national waste management decision-making process in Korea.

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cadmium, mercury, polybrominated diphenyl esters) (Huo et al., 2007; Wong et al., 2007; Scharnhorst et al., 2007; Hidy et al., 2011).

In response to growing concern over WEEE, many countries are working to establish proper treatment and recycling processes to reduce the quantity of WEEE that is disposed and to recover valuable resources. Unlike municipal solid waste, WEEE management systems have not been well established in most countries. Many recent studies have been published to address potential problems associated with WEEE management (He et al., 2006; Liu et al., 2006; Musson et al., 2006; Babu et al., 2007; Kahhat et al., 2008; Yang et al., 2008; Jang, 2010; Hidy et al., 2011).

In 2002, the Korea Ministry of Environment (Korea MOE) modified the Act on the Promotion of Conservation and Recycling of Resources for effective collection and recycling of waste materials (Korea MOE, 2002). The Act went into effect in 2003, and Korea introduced an extended producer responsibility (EPR) regulation for packaging materials and electronic devices. The EPR requires producers to take more responsibility for managing the environmental impacts of their products throughout their life cycles. In 2007, the Act on the Resource Recycling of Waste Electrical Electronic Equipment (WEEE) and End-of-life Vehicles (ELVs) was enacted (Korea MOE, 2007). The Korea WEEE Act regulates six hazardous substances (lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, polybrominated diphenyl esters) in electronics that disturb recycling and increase environmental impacts upon disposal, similar to the EU RoHS (the restriction of the use of certain hazardous substances) Directive (EU Directive, 2002a). However, the categories and types of WEEE regulated by the WEEE Act are still very limited and include only 10 electrical and electronic devices (i.e., refrigerators, washing machines, televisions, air conditioners, computers, printers, facsimiles, audio equipment, copy machines, and mobile phones). The EU WEEE directive consists of 10 categories with a total of 96 devices or types of equipment including large and small home appliances, information technology and telecommunications equipment, lighting equipment, medical devices, automatic dispensers, and others categories (EU Directive, 2002b). Unlike the European WEEE directive, current management policies and regulations in Korea have focused on large home appliances and limited IT products (e.g., computers, printers, mobile phones). The categories and items regulated by the EPR system under the WEEE Act need to be expanded, including small home appliances (e.g., vacuum cleaners, coffee makers) and other IT products (e.g., MP3 players, game players).

This study was intended to assess the potential of waste electronic devices or products that may become target WEEE for recycling and management in Korea. Four WEEE categories were selected for the evaluation process: new WEEE including large-sized home appliances, information and communication technology (ICT) devices, small and medium-sized household electronic devices, and audio and video equipment. Although these types of waste devices or equipment may not comprise a large proportion of WEEE streams, they merit special attention due to concerns over the hazards they pose to the environment upon disposal (Aizawa et al., 2008). Whether these devices or equipment should be included in WEEE regulations may depend on economic, environmental, and social factors such as the presence of proper recycling technology, generation rates (or emission rates), potential economic values, the presence of toxic chemicals and valuable metals, and the potential environmental impacts of the devices.

There is an urgent need to identify the ranking of new target WEEE for mandatory recycling and management in Korea. However, selecting an appropriate WEEE to be regulated can be a challenging and subjective task for waste management policy-makers, especially since waste management professionals and policy-makers often lack precise and objective decision-making procedures and evaluation criteria. Therefore, integrating objective and quantitative tools into the evaluation procedure enables decision-makers to efficiently and objectively identify the most appropriate WEEE to be recycled. In order to rank the target devices, we introduced the Delphi method and analytical hierarchy process (AHP) as a tool in the policy-making process for WEEE recycling. AHP modeling was used to determine the criteria weights and establish an evaluation model. The Delphi method was employed to identify objective evaluation criteria for selecting WEEE to be recycled.

A number of studies have examined the adoption of the AHP method for environmental management. Randall et al. (2004) adopted the AHP method for management of surplus elemental mercury in the US. Cram et al. (2006) used the AHP method to prioritize the same vegetation types based on endemic species. Hsu et al. (2008) utilized the AHP method to select the proper companies for medical waste disposal using interviews with medical waste experts by the Delphi method. Chang et al. (2009) combined the geographic information system (GIS) and fuzzy AHP method to search for the most appropriate distribution strategy in Taipei, Taiwan. Wang et al. (2009) used the AHP method to lower the complexity of waste management systems in order to select the appropriate solid waste landfill site. Lin et al. (2010) adopted the AHP method to determine the relative priorities of the addition of new mandatory recycled waste in Taiwan.

2. Background of WEEE management in Korea

The republic of Korea, with a population of approximately 50 million people, has experienced high environmental pollution loadings due to its rapid industrial development over the past several decades. The Korea's rapid economic growth, combined with its thriving electronics and information technology industry, fueled by such Korean electronics companies as SAMSUNG and LG, has become the major driving force for the expansion of domestic markets for electrical and electronic products. Recent statistics show that as of 2011, more than 52 million mobile phones, 24 million televisions, 17 million refrigerators, and 12.8 million computers were in use in Korea (KPE, 2012).

Determining life spans of electronic devices is central to estimating the potential rate of WEEE generation. Estimates are usually based on domestic demand for electronic devices and their average life span (i.e., the length of the time between the initial purchase of an electronic device and the time it completes its useful life). Life spans vary depending upon the type of device, economic and market conditions, age, and cultural behavior. It was estimated that the average life spans of the devices studied were 7.8 years for refrigerators, 7.8 years for washing machines, 7.4 years for televisions, and 6.0 years for air-conditioners. Shorter life spans were found for personal computers (4.0 years), notebook computers (4.0 years), printers (4.3 years), and mobile phones (2.4 years) (Jang and Lim, 2007; Jang, 2010).

By combining sales data (or domestic demand) with life span assumptions for each product, the total estimated number of units (or sometimes the corresponding weight) of a particular electronic device that is retired for waste management via reuse and refurbishment, recycling, export, or disposal (i.e., the amount of WEEE retired) can be estimated. The estimated amount of WEEE generated is determined by the sum of the retired amount of WEEE subtracted from the volume of WEEE that is reused, loaned, or stored at households. Based on the assumptions above, the retired and generated rate of WEEE in Korea can be estimated. For example, in this study, it was estimated that among 52 million mobile phones in use, more than 22 million mobile phones were

Table 1
Target recycling rates and accomplishment of WEEE recycling by the EPR system in Korea.

Type of WEEE	2009			2010			2011		
	Domestic demand	EPR target rate	Amount recycled by producers	Domestic demand	EPR target rate	Amount recycled by producers	Domestic demand	EPR target rate	Amount recycled by producers
Refrigerators	222,474	45,830	58,636	234,430	51,809	64,618	231,792	57,948	62,568
Washing machines	95,470	24,918	26,046	107,136	29,356	29,215	97,884	27,897	27,885
Televisions	74,214	11,874	18,544	86,300	16,397	21,491	73,821	15,502	19,585
Air-conditioners	126,979	2921	2887	128,790	3091	3064	146,862	3525	4060
Computers	47,605	5284	8383	54,571	6712	9790	55,506	7771	7141
Audio equipment	4901	760	685	4667	793	711	4157	769	788
Mobile phones	3,206	635	629	3537	778	731	3302	759	619
Copying machines	4636	617	588	5732	814	994	5682	852	1002
Facsimiles	468	57	117	525	70	129	365	55	70
Printers	11,929	1420	1938	15,097	1963	2462	14,606	2191	2298
Total	591,882	94,316	118,453	640,785	111,783	133,205	633,977	117,269	126,016

Recycling target rates by EPR and the amount of WEEE recycled in Korea between 2009 and 2011.
Source: Korea KEC, 2012

retired in 2011 only, while more than 8 million of the mobile phones that were generated could be reused or recycled.

Table 1 presents the domestic demand, EPR target rate, and actual recycling rates of WEEE between 2009 and 2011 in Korea under the EPR system. The Korea MOE determine the annual mandatory recycling rate of each product, based on target recycling rates over the previous years, the amount of electrical and electronic products shipped from the warehouse, and recycling market conditions. The annual amount of EPR mandatory recycling rate is determined by the annual amount of electrical and electronic products that are sold in domestic market multiplied by the annual mandatory recycling rate. For example, in 2011, the Korea MOE determined that the amounts of recycling EPR target rates were 57,948 tons for refrigerators, 27,897 tons for washing machines, 15,502 tons for televisions, and 3,525 tons for air conditioners. The amounts of most WEEE products producers recycled generally exceeded their mandatory target rates.

Fig. 1 shows the trends of recycling rates of WEEE between 2006 and 2011. The quantity of WEEE recycled generally increased over the years because of the increased EPR target rate and regulation. The amount of WEEE recycled in 2011 was approximately 5.4% lower than the amount of WEE recycled in 2010. When compared with the average WEEE recycling rate (6.6 kg/person/yr) of advanced EU countries in 2010, the recycling rate (2.8 kg/person/yr) of WEEE in Korea as of 2011 is still much lower (EC, 2013).

In recent years, the national government and local governments have employed various methods to recycle WEEE. These include the establishment of collection systems for diverse e-waste devices, setting long-term national target rates for recycling of WEEE, assigning mandatory collection rates to electronics retailers and distributors, planning for the expansion of mandatory WEEE recycling by the EPR system, increasing the role of local government in WEEE collection, and developing a recycling technology roadmap for WEEE. If these WEEE collection and recycling efforts are improved, the amount of WEEE that is recycled will continually increase over time. Starting in 2012, some municipalities started to collect small and medium-sized WEEE in curbside collection containers free of charge in residential areas. In some municipalities, there is a free door-to-door collection service available for households who call on-line service to pick up large, obsolete household appliances by producers. In 2012, mandatory collection rates were assigned to larger electronics retailers and distributors for recycling of the 10 EPR items regulated by the Korea MOE. In 2013, the required collection rates for retailers range from 0.6% of air

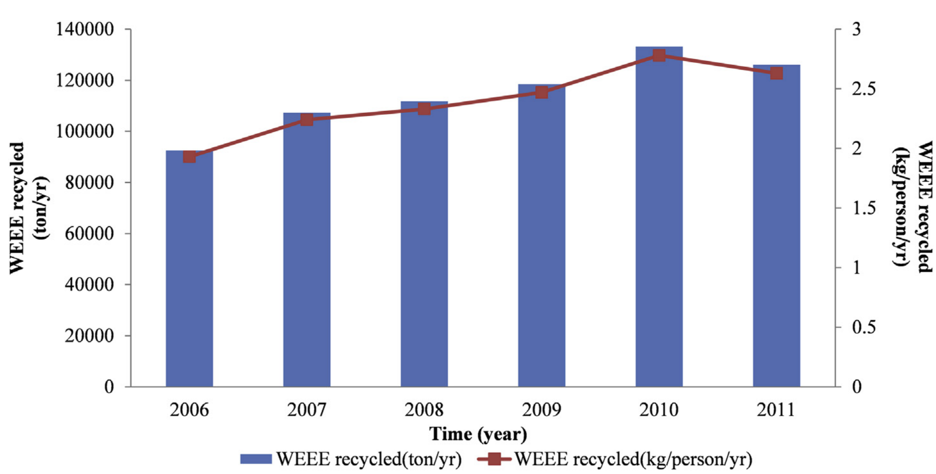

Fig. 1. Recycling rates of WEEE in Korea between 2006 and 2011.

conditioners to 25% of televisions that are sold to consumers (Korea MOE, 2013). In addition, there is growing interest in urban mining from WEEE in Korea due to rapidly increasing prices stemming from the depletion of valuable and rare metals (e.g., palladium, lithium, tin, cobalt, nickel, indium, titanium, neodymium, tantalum, and other metals) (Lee et al., 2007).

3. Methodology

In this study, the methodology included gathering data associated with annual domestic demand for (or sales of) selected home appliances and electronic devices, site visits, questionnaire surveys for the Delphi-AHP method, interviews and conversations, and a review of available literature. Site visits to locations including WEEE recycling centers and facilities, regulatory agencies, and the Korea Association of Electronics & Environment (Korea AEE), a producer responsibility organization (PRO), were made to support and supplement information gathered by the surveys. Interviews and conversations with environmental regulatory agencies, recycling industry experts, and PRO committees were conducted to obtain the details of recent progress and development associated with WEEE management. Available literature was also obtained and examined to compare WEEE collection and recycling rates in Korea with other countries and regions. An attempt was made to select the priority types of WEEE to be targeted for mandatory recycling in the EPR system in Korea. In addition to adopting the Delphi method to identify evaluation criteria, this study used the AHP to establish a model for selecting the priority devices. The theoretical approaches and backgrounds that were adopted are described below.

3.1. Delphi method

In this study, we used the Delphi and AHP methods to select products for the expansion and promotion of WEEE recycling in order to present priority rankings based on selected evaluation criteria. Our goal was to use the criteria and results as a basis to develop regulatory measures for the selection of products for inclusion in the expansion and maximization of WEEE recycling. We conducted an expert survey for appropriate evaluation criteria using the Delphi method, interviewing a total of 10 experts from government, academia, and industry sectors in order to prioritize products for WEEE recycling. Based on the evaluation criteria selected for priority ranking, the AHP method was used to determine the relative importance of each product. We also collected evidence from expert interviews, site visits, and the available literature on generation rates (waste volume or emission rate), recycling rates, valuable metal content, and ease of establishing a collection system.

To determine the evaluation criteria to prioritize the products, we applied the Delphi method. The Delphi method is used to repeatedly obtain expert opinions until there is a comprehensive consensus on selecting projects, predicting problems, and resolving problems (Delbecq et al., 1975). In contrast to the commonly used method of brainstorming, in which experts convene in one place to reach a consensus, the Delphi method overcomes the disadvantage of an outspoken person or collective group thinking dominating the outcome by allowing experts to respond anonymously. In this study, we primarily used e-mail to obtain opinions and conducted expert surveys twice (1st expert survey and 2nd expert survey). Specifically, we analyzed the coefficient of variation (CV) for the expert surveys and content validity ratio (CVR). In these evaluation criteria, when the CV value is less than 0.5, additional surveys are stopped (Dajani et al., 1979). The CVR developed by Lawshe (1975) and recalculated by Wilson et al. (2012) measures agreement among survey raters as to how essential a particular factor or item is. The CVR ranges from +1 to −1. A higher positive value is used as an indicator that survey experts were in agreement that a factor or item was essential. Generally, a CVR that is greater than 0.29 can be considered to be an appropriate evaluation level. The coefficient of variation is the ratio of the standard deviation to the mean. Using the CV can make it easier to compare the overall precision of the data obtained, as shown in Equation (1):

$$\text{Content Validity Ratio (CVR)} = \frac{\text{NE} - N/2}{N/2} \tag{1}$$

where Ne = the number of survey experts indicating that a factor or item is “essential” and N = the total number of survey experts.

3.2. AHP method

When the environment is more complex and more factors need to be considered in decision-making process, it becomes difficult to select appropriate alternatives. Hence, in this study, we introduced the concept of hierarchical pair-wise comparison by applying the AHP method. By using AHP, the decision-making process can be divided into several hierarchical levels, and by using a pairwise comparison at each level, a decision can be made based on the knowledge and experience of many experts (Saaty, 1996). AHP assesses the priorities of multiple alternatives under various valuation criteria.

AHP calculates the relative importance of decision-making through stratification and class analysis. If the population to be studied is composed of many people, standards and periods, AHP is useful because it can separate these criteria during analysis. AHP uses class analysis and problem stratification to determine relative importance (Saaty, 1996). The classes of decision-making are determined-in the first phase, which may be the most important step in AHP application. The second phase collects evaluation data using pairwise comparison between decision-making factors, and also draws the matrix through pairwise comparison in a subclass that is dedicated to accomplishing the goals of each factor.

The next phase uses a matrix of pairwise comparison to estimate the weights and relative importance of the determination factors within each class. The $w_{1,}$ w_2, w_3, and w_n are calculated, indicating the effects and preference of valuation standards c_1, $c_{2,}$ c_3 and c_n by using the a_{ij} value acquired during the pairwise comparison. Saaty (1996) proposed the eigenvalue method as a weight evaluation, as shown in Equation (2):

$$A' \cdot W' = \lambda_{\max} \cdot W' \tag{2}$$

where A is the square matrix resulting from pairwise comparison, $\lambda_{\max}$ is the maximum eigenvalue, and w is the eigenvector.

The measurement of consistency is developed using two characteristics. One is that matrix A has greater consistency as $\lambda_{\max}$ gets closer to n. The other is that $\lambda_{\max}$ values are always bigger than or the same as n, as shown in Equations (3) and (4):

$$\text{Consistency Index (CI)} = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

$$\text{Consistency Ratio (CR)} = \frac{\text{CI(Consistency Index)}}{\text{RI(Random Index)}} \tag{4}$$

The random index is determined by the size of n. In cases when the consistency is perfect, $\lambda_{\max}$ is equal to n so that CI becomes 0 and CR is 0. On the contrary, as the consistency of judgments gets

Table 2
CV and CVR results of final evaluation criteria.

Criteria	CV	CVR
High waste generation rate or waste volume	0.14	0.80
Low recycling cost	0.24	0.40
Availability of recycling technology	0.15	0.56
High valuable metal content	0.20	0.80
Established collection system	0.13	0.40
Similarity to current Extended Producer's Responsibility (EPR) item	0.21	0.40
Similarity to current plastic disposal fee charge items	0.31	0.40

lower, λ_{max} becomes bigger than n and the CI and CR are both larger than 0. Saaty (1996) advised that CR is consistent in cases where it is smaller than or equal to 0.1. If it exceeds 0.1, the pairwise comparison needs to be done again or the questionnaire has to be revised.

In the last phase, the relative weights of decision-making factors are integrated to evaluate the total ranks of several different alternatives. The total importance of vectors that determine the priorities of alternatives at the bottom of the list are computed to achieve the purposes of determination at the top, which makes it possible to combine the weights of each class acquired in the third phase. The weighting equation of alternatives is shown in Equation (5):

$$\omega_i = \sum(\omega_j)(\mu_j^i) \quad (5)$$

ω_i : Total weight of the alternative i, ω_j : Relative weight of the valuation standard j, μ^i_j : Weight of the alternative i to the valuation standard j

In this study, we used the AHP method to collect expert opinions from the Korea MOE, academia, and industry sectors in the field of WEEE management and recycling. The AHP survey was administered to the experts; the results were analyzed and presented using Expert Choice 2000 software. If the importance of a specific evaluation criterion changes, the priority of product selection also can vary. Therefore, to determine the effect of the evaluation criteria on the results, we also performed sensitivity analysis for each criterion. These methods improve the efficiency of the decision-making process.

4. Results and discussion

4.1. Evaluation criteria by the Delphi method

We surveyed 10 experts in the field of WEEE recycling twice using the Delphi method in order to determine the evaluation criteria for prioritizing recycling of waste electronic and electrical products. Twelve criteria were selected by the first Delphi survey.

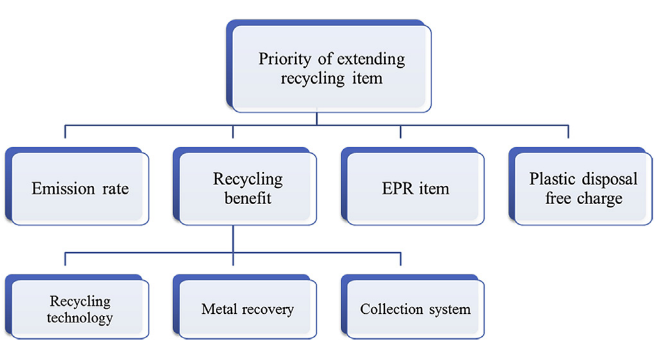

Fig. 2. Overall hierarchical structure of the AHP framework.

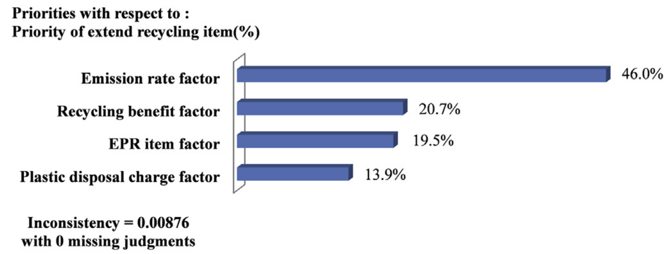

Fig. 3. Relative importance of 1st evaluation criterion.

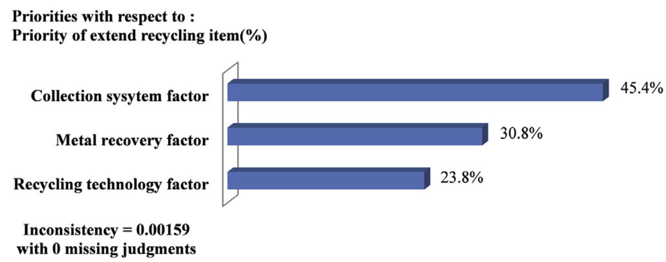

Fig. 4. Relative importance of 2nd evaluation criterion.

Seven final criteria were selected by the second Delphi survey, including high waste generation rate (or emission rate), low recycling cost, availability of recycling technology, established collection system, high valuable metal content (recovery potential), similarity to products regulated by current EPR items, and similarity to current plastic disposal fee charge items regulated by the Korea MOE. The CV and CVR results of the seven final criteria are shown in Table 2. Each evaluation criterion met the required levels of CV (less than 0.5) and CVR (greater than 0.29). Based on the results, similar criteria were grouped together hierarchically according to primary and secondary criteria, as shown in Fig. 2. In the hierarchical structure, the overall goal was to identify the priority of mandatory recycling items to be targeted. Level 1 (1st evaluation criteria) represents the four evaluation criteria (emission rate, recycling benefit, similarity to current EPR items, and similar products in the current plastic disposal fee charging system). Subcriteria (2nd evaluation criteria) under the recycling benefit include availability of recycling technology, higher valuable metal recovery, and establishment of a feasible collection system.

4.2. Results of AHP analysis

It is difficult to determine the priority ranking (importance) of each evaluation criterion by brainstorming or using the Delphi

Table 3
Products to be evaluated by the AHP method.

Category	Products
Large home appliances	Refrigerator, dryer, oven, water cooler/heater, freezer
IT and communication devices	Mobile (cellular) phone, electronic dictionary, scanner, telephone
Audio/video equipment	Television, camera, DVD, projector, portable GPS device, MP3 player, portable multimedia player, electric musical instruments, game console, home theater system
Medium-sized or small consumer electronics	Vacuum cleaner, microwave oven, electric rice cooker, heating fan, electric fan, air purifier, humidifier, dehumidifier, bidet, electrical mixer, coffee maker, electric iron, table lamp or stand

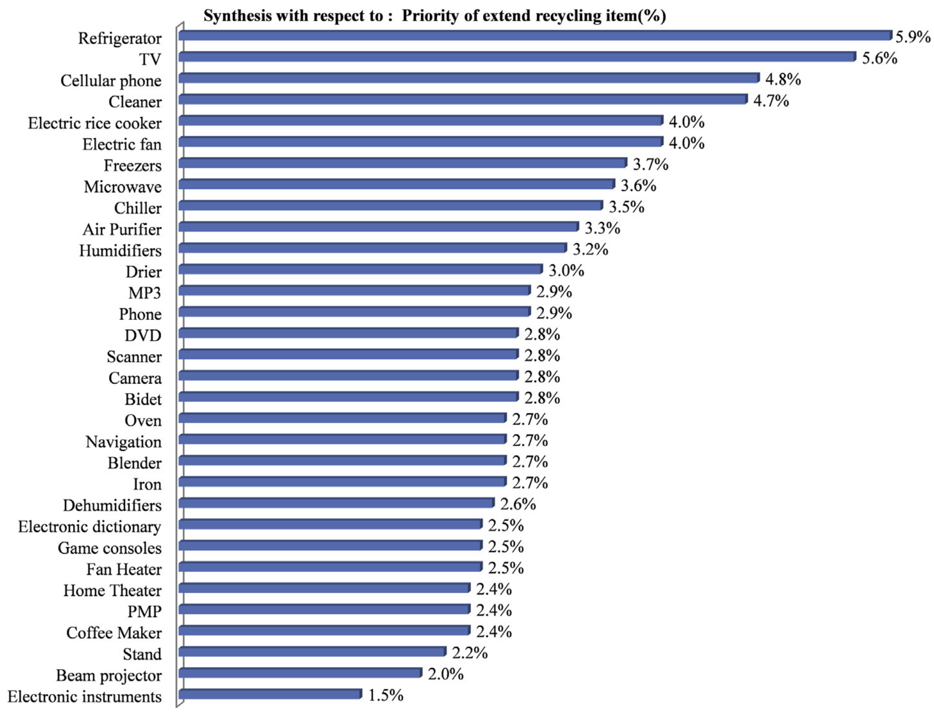

Fig. 5. Priority of WEEE to be recycled with relative importance.

method. However, by using AHP analysis, the relative importance of each evaluation criterion can be quantified and can ultimately lead to the selection of alternatives (in this study, the priority ranking of alternative products to be recycled). The relative importance of each evaluation criterion was determined, as shown in Fig. 3. The results showed that the emission rate or generation rate was the most important factor with a weighted percentage of 46.0%, followed by the recycling benefit factor (20.7%) and similarity to products currently regulated by the EPR item (19.5%). Therefore, in order to minimize the effort and time spent in the process of prioritizing the products, the factor to be considered first is the emission rate or generation rate. Fig. 4 shows the relative importance of the secondary evaluation criteria that were determined to be subordinate to recycling benefit, using the AHP method. Similar to the results listed above, the collection system is a very important factor (45.5%), followed by metal recovery (30.8%) and recycling technology (23.8%).

Before starting the AHP method, the Korea MOE suggested 32 potential WEEE candidates to be prioritized during expert interviews, as shown in Table 3. Among these, three EPR products (i.e., refrigerators, TVs, and mobile or cellular phones) were also included in expert surveys for the relative comparison of products with future mandatory target recycling items. Based on the primary and secondary selection evaluation, the results of the priority ranking of the products are listed in Fig. 5. After being evaluated for relative importance, the 32 products in Fig. 5 were ranked according to their overall priority among recycling items. In addition to the three current WEEE that have been targeted for recycling (refrigerators, TV, and mobile phones), the top ten priority items to be added to the mandatory target recycling EPR list include vacuum cleaners, electric fans, electric rice cookers, large freezers, microwave ovens, water purifiers, air purifiers, humidifiers, kitchen dryers, and telephones in order (from the first to the last).

Table 4 presents the top ten priority ranking results based on the factor only, with all factors considered. The emission rate or generation rate was considered to be the most important factor in this analysis. The results show that when only the emission rate or generation rate is considered, it is optimal to include vacuum cleaners, electric fans, electric rice cookers, microwave ovens, telephones, humidifiers, freezers, camera, electric irons, and water coolers/heaters (in order from first to last) in the expansion of recycling target items. When all the factors are considered, the top five priority items include vacuum cleaners, electric fans, electric rice cookers, freezers, and microwave ovens.

Table 4 also shows the top 10 priority items by the "generation rate or emission rate" factor, comparing them with actual generation rates of small-size electronics and appliances (in order from first to last) by unit and mass reported by other researchers (Kim

Table 4
Priority ranking among products considered for expanded recycling.

Rank	By all factors	By waste generation rate or emission rate	Waste generation rate (by mass)[a]	Waste generation rate (by unit)[a]
1	Vacuum cleaner	Vacuum cleaner	Vacuum cleaner	Telephone
2	Electric fan	Electric fan	Electric mixer	Vacuum cleaner
3	Electric rice cooker	Electric rice cooker	Electric fan	Electric mixer
4	Freezer	Microwave oven	Electric rice cooker	Electric fan
5	Microwave oven	Telephone	Telephone	Electric rice cooker
6	Water purifier	Humidifier	Humidifier	Humidifier
7	Air purifier	Freezer	Microwave oven	Microwave oven
8	Humidifier	Camera	Coffee maker	Electric iron
9	Kitchen dryer	Electric iron		
10	Telephone	Water purifier		

[a] Source: Kim et al., 2008.

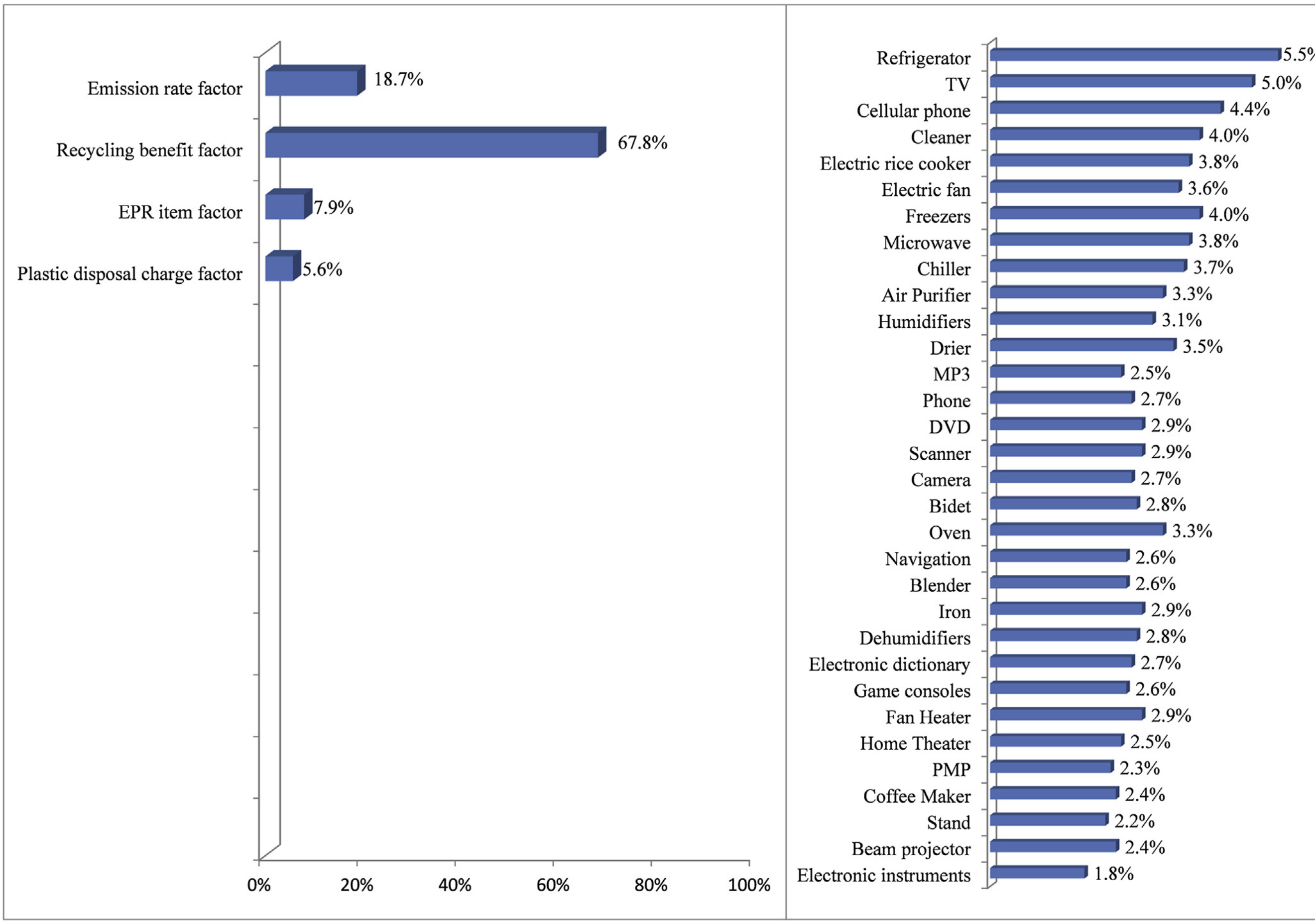

Fig. 6. Results of sensitivity analysis with respect to changes of relative importance of evaluation criteria.

et al., 2008). It is found that the order of the top 10 products in our study is very similar to that of the generation rates of small appliances reported by Kim et al. (2008) (Table 4).

4.3. Results of sensitivity analysis

To improve the decision-making process, sensitivity analysis was used to analyze the way changes in the importance of factors affect on the results. For example, if the importance of the recycling benefit factor increases from 20.7% to 67.8%, the priority ranking of products to be included in the expansion of target recycling items also changes, as shown in Fig. 6. Vacuum cleaners, large freezers, electric rice cookers, microwave ovens, water purifiers, electric fans, dryers, air purifiers, electric ovens, and humidifiers have been identified as the top ten items in order from first to last. Thus, the priority ranking results have also changed due to the change in the importance of the factors.

In the coming years, the Korea MOE plans to add 16 new categories of WEEE to be mandatorily recycled by the EPR system, based on the results of this study as well as a series of discussions among stakeholders (e.g., producers, NGOs, the recycling industry, and government). The target items to be considered for mandatory recycling include water purifiers, air purifiers, vacuum cleaners, microwave ovens, bidets, electric rice cookers, heating fans, electric fans, humidifiers, electric irons, electric cookers, kitchen dryers, video cassettes, electric mixers, food waste drying machines, and water softeners.

5. Conclusion

In an ever-changing modern electronic and information technology society, numerous electrical and electronic devices are generated for consumption and eventual disposal. In order to effectively increase WEEE recycling rates imposed by the WEEE Act, the target WEEE list should be gradually expanded, based on social infra-structure and consensus among stakeholders. However, selecting an appropriate WEEE to be regulated for recycling and proper treatment is frequently a challenging and subjective task because waste management decision-makers often lack precise and objective data and evaluation criteria.

In this study, we used the Delphi method and AHP to determine the priority of target recycling products for the expansion and promotion of WEEE recycling. Expert surveys were performed to determine the evaluation criteria and expand the list of EPR products to be mandatorily recycled. Evaluation criteria were first selected based on the results of the primary and secondary Delphi surveys; the results were classified hierarchically, grouped by similarities. The primary evaluation criteria included generation rate or emission rate (46.0%), followed by recycling benefit (20.7%), and similarity to products currently regulated by the EPR system (19.5%). The secondary evaluation criteria were collection system (45.4%), followed by valuable metal content (30.8%) and recycling technologies (23.8%). Applying the above criteria using the AHP, the results indicate that the top 10 target recycling products for the expansion of the WEEE list were found to be vacuum cleaners, electric fans, electric rice cookers, large freezers, microwave ovens, water purifiers, air purifiers, humidifiers, kitchen dryers, and standard telephones in order from first to last.

The application of Delphi and AHP modeling proved to be an efficient tool for the WEEE decision-making process. Integrating quantitative methods into the evaluation procedure enabled decision-makers to determine WEEE priorities for recycling objectively and efficiently. Recent WEEE regulation efforts along with better recycling technology would increase WEEE collection and recycling rates through diverse collection programs, encourage producers to develop more environmentally sustainable products, and require producers to take extended responsibility for the recycling of their products. Finally, it should be noted that the relative importance of evaluation criteria used in WEEE analysis can change due to better collection systems, innovations, and new recycling technologies. Therefore, this study's evaluation criteria and the factors used to determine its relative importance should be updated and further refined for evaluation in waste management arena.

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References

Aizawa, H., Yoshida, H., Sakai, S., 2008. Current results and future perspective for Japanese recycling of home appliances. Resour. Conserv. Recy. 52, 1339–1410.

Babu, B., Parandu, A., Basha, C., 2007. Electrical and electronic waste: a global environmental problem. Waste Manage. Res. 25, 307–318.

Chang, N.-B., Chang, Y.-H., Chen, H.-W., 2009. Fair fund distribution for a municipal incinerator using GIS-based fuzzy analytic hierarchy process. J. Environ. Manage. 90, 441–454.

Cram, S., Sommer, I., Morales, L., Oropeza, O., Carmona, E., González-Medrano, F., 2006. Suitability of the vegetation types in Mexico's Tamaulipas state for the siting of hazardous waste treatment plants. J. Environ. Manage. 80, 13–24.

Dajani, J., Sincoff, M., Talley, W., 1979. Stability and agreement criteria for the termination of Delphi studies. Technol. Forecast. Soc. 13, 83–90.

Delbecq, A.L., van de Ven, A.H., Gustavson, D.H., 1975. Group Techniques for Program Planning: a Guide to Nominal Group and Delphi Processes. Scott Foresman and Company, Glenview, Illinois.

European Commission (EC), 2013. Environmental Data Centre on Waste Electrical and Electronic Waste (WEEE). <http://www.epp.eurostat.ec.europa.eu> (accessed 14.01.13.).

EU Directive, 2002a. 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances (RoHS) in waste electrical and electronic equipment. Off. J. L037, 0019–0023.

EU Directive, 2002b. 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE)-Joint Declaration of the European Parliament, the Council and the Commission relating to Article 9. Off. J. L037, 0024–0039.

He, W., Li, G., Ma, X., Wang, H., Huang, J., Xu, M., Huang, C., 2006. WEEE recovery strategies and the WEEE treatment status in China. J. Hazard. Mater. 136, 502–512.

Hidy, G., Alcorn, W., Clarke, R., Smith, D., Thomas, V., 2011. Environmental issues and management strategies for waste electronic and electrical equipment. J. Air Waste Manage. 61, 990–995.

Hsu, P.-F., Wu, C.-R., Li, Y.-T., 2008. Selection of infectious medical waste disposal firms by using the analytic hierarchy process and sensitivity analysis. Waste Manage. 28, 1386–1394.

Huo, X., Peng, L., Xu, X., Zheng, L., Qiu, B., Qi, Z., Zhang, B., Han, D., Piao, Z., 2007. Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environ. Health Persp. 115, 1113.

Jang, Y., 2010. Waste electrical and electronic equipment (WEEE) management in Korea: generation, collection, and recycling systems. J. Mater. Cycles Waste Manage. 12, 283–294.

Jang, Y., Lim, S., 2007. National Survey of E-waste by Material Flow Analysis. Final Report Submitted to Korean Association of Electronics Environment, Korea (in Korean).

Kahhat, R., Kim, J., Xu, M., Allenby, B., Williams, E., Zhang, P., 2008. Exploring e-waste management systems in the United States. Resour. Conserv. Recy. 52, 955–964.

Kim, I., Cho, B., Kim, S., Lee, S., Kim, A., 2008. A Study on Current Trend in Generation and Recycling of Small Household Appliance. Final Report Submitted to Korean Association of Electronics Environment, Korea (in Korean).

Korea Ministry of Environment (Korea MOE), 2002. The Act on the Promotion of Conservation and Recycling of Resources. Korea MOE.

Korea Ministry of Environment (Korea MOE), 2007. The Act on the Resource Recycling of Waste Electrical Electronic Equipment (WEEE) and End-of-life Vehicles (ELVs).

Korea Ministry of Environment (Korea MOE), 2013. Collection and Recycling Target Rate of WEEE in 2013. Korea MOE regulation No 2012–251.

Korea Environmental Coporation (KEC), 2012. Annual Report of Recycling of WEEE in Electric and Electronic Equipment and End-of-Life Vehicle in Eco-Assurance (EcoAS). Korea (in Korean).

Korea Power Exchange (KPE), 2012. Penetration Rate of Home Appliances and Behaviors of Korean Consumers' Survey for Electricity. Annual report, KPE. (in Korean).

Lawshe, C.H., 1975. A quantitative approach to content validity. Personnel Psychol. 28, 563–575.

Lee, J.-C., Song, H.T., Yoo, J.-M., 2007. Present status of the recycling of waste electrical and electronic equipment in Korea. Resour. Conserv. Recy. 50, 380–397.

Lin, C., Wen, L., Tsai, Y., 2010. Applying decision-making tools to national e-waste recycling policy: an example of analytic hierarchy process. Waste Manage. 30, 863–869.

Liu, X., Tanaka, M., Matsui, Y., 2006. Electrical and electronic waste management in China: progress and the barriers to overcome. Waste Manage. Res. 24, 92–101.

Musson, S., Vann, K., Jang, Y., Mutha, S., Jordan, A., Pearson, B., Townsend, T., 2006. RCRA toxicity characterization of discarded electronic devices. Environ. Sci. Technol. 40, 2721–2726.

Randall, P., Brown, L., Deschaine, L., Dimarzio, J., Kaiser, G., Vierow, J., 2004. Application of the analytic hierarchy process to compare alternatives for the long-term management of surplus mercury. J. Environ. Manage. 71, 35–43.

Saaty, T.L., 1996. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. RWS Publications, Pittsburgh.

Scharnhorst, W., Ludwig, C., Wochele, J., Jolliet, O., 2007. Heavy metal partitioning from electronic scrap during thermal End-of-Life treatment. Sci. Total Environ. 373, 576–584.

Wang, G., Qin, L., Li, G., Chen, L., 2009. Landfill site selection using spatial information technologies and AHP: a case study in Beijing, China. J. Environ. Manage. 90, 2414–2421.

Wilson, F., Pan, W., Schumsky, D., 2012. Recalculation of the critical values for Lawshe's content validity ratio. Meas. Eval. Couns. Dev. 45, 197–210.

Wong, M., Wu, S., Deng, W., Yu, X., Luo, Q., Leung, A., Wong, C., Luksemburg, W., Wong, A., 2007. Export of toxic chemicals—a review of the case of uncontrolled electronic-waste recycling. Environ. Pollut. 149, 131–140.

Yang, J., Lu, B., Xu, C., 2008. WEEE flow and mitigating measures in China. Waste Manage. 28, 1589–1597.

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Estimation of end of life mobile phones generation: The case study of the Czech Republic

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ABSTRACT

The volume of waste electrical and electronic equipment (WEEE) has been rapidly growing in recent years. In the European Union (EU), legislation promoting the collection and recycling of WEEE has been in force since the year 2003. Yet, both current and recently suggested collection targets for WEEE are completely ineffective when it comes to collection and recycling of small WEEE (s-WEEE), with mobile phones as a typical example. Mobile phones are the most sold EEE and at the same time one of appliances with the lowest collection rate. To improve this situation, it is necessary to assess the amount of generated end of life (EoL) mobile phones as precisely as possible. This paper presents a method of assessment of EoL mobile phones generation based on delay model. Within the scope of this paper, the method has been applied on the Czech Republic data. However, this method can be applied also to other EoL appliances in or outside the Czech Republic.

Our results show that the average total lifespan of Czech mobile phones is surprisingly long, exactly 7.99 years. We impute long lifespan particularly to a storage time of EoL mobile phones at households, estimated to be 4.35 years. In the years 1990–2000, only 45 thousands of EoL mobile phones were generated in the Czech Republic, while in the years 2000–2010 the number grew to 6.5 million pieces and it is estimated that in the years 2010–2020 about 26.3 million pieces will be generated. Current European legislation sets targets on collection and recycling of WEEE in general, but no specific collection target for EoL mobile phone exists. In the year 2010 only about 3–6% of Czech EoL mobile phones were collected for recovery and recycling. If we make similar estimation using an estimated average EU value, then within the next 10 years about 1.3 billion of EoL mobile phones would be available for recycling in the EU. This amount contains about 31 tonnes of gold and 325 tonnes of silver. Since Europe is dependent on import of many raw materials, efficient recycling of EoL products could help reduce this dependence. To set a working system of collection, it will be necessary to set new and realistic collection targets.

1. Introduction

Waste electrical and electronic equipment (WEEE) is one of the priority waste streams of the European Union (EU) (Crowe et al., 2003). Main reasons for the concern are very fast growth of the waste stream and its complex composition with a potential negative effect on environment and human health (European Commission-WEEE Directive, 2003). WEEE stream can be divided into large waste electrical and electronic equipment (e.g. refrigerators, washing machines, etc.) and small waste electrical and electronic equipment (s-WEEE) with mobile phones as a typical example. As s-WEEE, mobile phones can seem to have a minor share on the amount of WEEE generated. However, considering over 5.37 billion of world mobile phone subscriptions in the year 2010 (ITU, 2011a), their contribution to total environmental impacts of WEEE would not be negligible. Huisman et al. (2007) revealed that mobile phones are the most often sold appliances into the households. Moreover, the report shows that mobile phones are on average used for approximately 2 years, which causes a fast turnover on the market and leaves a significant amount of waste with specific properties and way of treatment.

EU legislation restricting the use of hazardous substances in electrical and electronic equipment (European Commission-RoHS Directive, 2003) and promoting the collection and recycling of such equipment (European Commission-WEEE Directive, 2003) have been in force since February 2003. Four years later, the highest collection rate 40% is gained for larger appliances, followed by about 25% collection rate for medium sized household appliances. Small appliances, with a few exceptions, are close to 0% collection (UNU,

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2007), e.g. less than 10% end-of-life (EoL) mobile phones are recycled in an appropriate way (RICS, 2011). The current fixed collection target of 4 kg per person per year does not properly reflect the amount of WEEE arising in individual Member States and is not ambitious enough for increasing collection of s-WEEE. The European Parliament adopted a recast of the WEEE Directive on 19 January 2012. From the year 2016, this recast changes the collection target to 45% of EEE placed on the market in three preceding years. In case of the Czech Republic (and other states of middle and eastern Europe), similar target will be valid from the year 2017, with the collection quota, minimum 40% of EEE placed on the market in three preceding years. Furthermore, after the year 2021 the target increases to 65% of EEE placed on the market in three preceding years or alternatively to 85% of WEEE arising in the Czech Republic. However, separate collection targets for s-WEEE are not included (European Parliament, 2012).

The main reason for the high importance of environmentally friendly treatment of mobile phones is their big content of both, dangerous and valuable substances. On one hand, cadmium from one mobile phone battery is sufficient to pollute 600,000 l of water (BBC, 2002). On the other hand, "non-collection" of EoL mobile phones means considerable amount of unrecovered raw materials, such as gold, silver and palladium. Mobile phone handsets with gold concentration reaching 300–350 g/tonne are significantly richer source of gold, compared to a typical primary ore mine, which will yield around 5 g/tonne of gold (Hagelüken and Corti, 2010). Up to 2008, cumulative sales of mobile phones numbered 7.2 billion, which equates to 170 tonnes of gold (Hagelüken and Corti, 2010), which could potentially be recovered. Moreover, Huisman (2004) revealed that in mobile phones, three–quarters of the environmental impacts result from the gold and palladium content. The change of material content in mobile phones is presented in Table 1.

The need of well working collection system in the Czech Republic of EoL mobile phones is boosted by the fact that it is one of the countries with highest share of mobile phones communication worldwide. In the year 2010, average number of mobile subscriptions per 100 inhabitants in developed countries was 114.2 (ITU, 2011a). Among these countries, the Czech Republic with 137.2 subscriptions per 100 inhabitants showed very high mobile phone penetration rate (ITU, 2011b). Moreover, within the EU, the Czech Republic has the highest proportion of mobile phone users, with 7 out of 10 inhabitants using only mobile communication (Directorate General Communication, 2010). This is in spite of the fact that history of Czech Mobile industry is relatively short. History started in 1991 when a first analogue network started to operate. However, mobile communication remained minimal until the year 1996, when digital mobile network of second generation started to operate (CSO, 2010a). In the year 2010 there were 4 mobile phone operators on the Czech market and mobile communication presented 80% of total volume of telecommunication (CSO, 2010a). Mobile phones surpassed fixed phone numbers already in the year 2000 and caused stagnation in this sector (CSO, 2010a). This trend can be seen in Fig. 1, which shows growth of the number of mobile phones in households in the years 1999–2009 (CSO, 2010a).

Table 1
Selected materials in mobile phone produced in the years 2001 and 2005 (Huisman, 2004; UNEP, 2009).

Material	Mass in mg per unit (2001)	Mass in mg per unit (2005)
Ag	244	150
Al	2914	8166
Au	38	18
Be	3	2
Bi	31	1
Br	941	427
Cr	345	1046
Cu	14,235	9996
Fe	8039	8399
Glass	10,594	7501
Ni	1124	3276
Pb	301	10
Pd	15	1
Sb	84	3
Sn	689	911
Zn	641	655

Considering above discussed consequences of mobile phone life cycle, there is a strong need for reliable empirical enquiries on the amount of EoL mobile phones generated. Yet, there is no such estimation available in the Czech Republic.

Due to aforementioned reasons, this paper aims to:

- Analyse mobile phones lifespan on the case of the Czech Republic;
- estimate EoL mobile phones generation in the Czech Republic in the years 1995–2020.

2. Literature review

As already mentioned, no reliable estimation of EoL mobile phones generation has been made by now in the Czech Republic. Worldwide, various approaches have been used to estimate generation of WEEE and EoL mobile phones in particular. Yang and Williams (2009) used logistic model-based forecast for EoL computers in the US. Lin (2008) described ownership model based on mass-balance to estimate EoL TVs, refrigerators, washing machines and air-conditioners generation in Taiwan. Dwivedy and Mittal (2010) focused on estimation for personal computers, televisions, refrigerators and washing machines. Walk (2009) forecasted quantities of EoL CRT appliances for German region. Oguchi et al. (2008) estimated waste production for 94 types of electronic and electrical equipment in Japan. Feszty et al. (2003) assessed quantities of WEEE in Scotland and Chung et al. (2010) in Hong Kong. Several authors chose material flow analysis for WEEE generation estimation such as Steubing et al. (2010), Yoshida et al. (2009) and Kang and Schoenung (2006). Several methods for the calculations of waste potential of WEEE, including Time step method, Market Supply method, Approximation formula and The Carnegie Mellon method are described in the study of EEA (Crowe et al., 2003). Another overview of estimation methods presented in Chancerel (2010), is shown in Table 2.

In all aforementioned methods, lifespan of electronic and electrical equipment (EEE) is essential information for the estimation. According to Oguchi et al. (2010), there are two approaches for estimation of commodity lifespan. One is the non-parametric approach, which does not assume any statistical distribution. The other one is the parametric approach, which assumes a statistical distribution function such as normal distribution, log-normal distribution, or Weibull distribution, and then approximates the observed data to the statistical distribution function. Generally there are four basic methods for lifespan estimation. Estimation from the number of discarded products for each lifespan, estimation from the number of products in use for each age of product, estimation from the number of products in use for each age at the beginning and the end of a certain period and estimation from the total number of products in use according to the mass-balance principle (Murakami et al., 2010).

3. Materials and methods

In this paper, we have used a method proposed by Nordic Council of Ministers (2009), with a different lifespan determina-

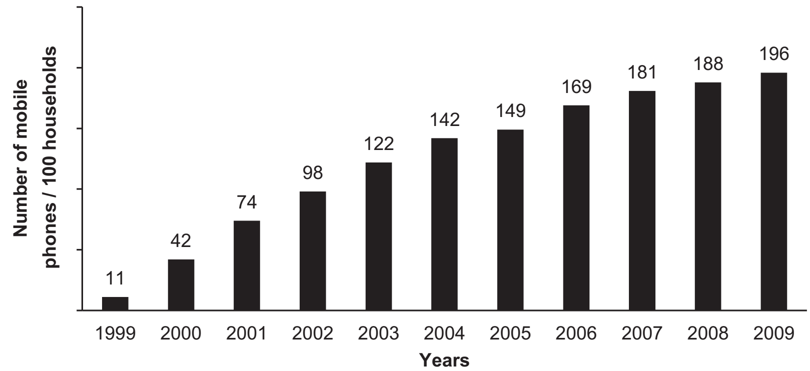

Fig. 1. Number of mobile phones/100 households in the years 1999–2009 (CSO, 2010b).

Table 2
Methods of the estimation of WEEE generation (modified from Chancerel, 2010).

Method	Calculation	Required data			Applicable to		Accuracy
		Sales	Stock*	Lifespan	Saturated markets	Dynamic markets	
Distribution delay	Sales in previous years and distribution of lifespan	x		x	x	x	High
Sales	Sales at t	x			x		Low
Simple delay	Sales at (t − lifespan)	x		x	x		Medium
Time step	Stock at (t − 1) − Stock at t + (Sales − WEEE) until t	x	x		x	x	High
Carnegie Mellon	Includes data on behaviour of end user (hibernation/reuse/disposal)	x		x	x	(x)	High
Batch leaching (Stock & lifespan)	Stock at t/lifespan (or other parameter α)		x	x	x		Low
Econometric analysis	Depending on GDP or other parameters						Low

* Stock = penetration rate in households x number of households + penetration rate in business x number of business.

tion. This method can be assigned to "distribution delay method" (Chancerel, 2010; Van der Voet et al., 2002). The method requires two types of input, firstly probable lifespan distribution of mobile phones and secondly volumes of mobile phones supplied to the market (both historical and future).

To determinate lifespan distribution, empirical data were used instead of specifying lifespan profile using Delphi method proposed by Nordic Council of Ministers (2009). Delphi method, considered as a semi-scientific method, is regarded as a simple, resources and time sparing method mainly in cases where lifespan for many types of EEE need to be determined (Nordic Council of Ministers, 2009). On the contrary, we analysed lifespan only for one kind of EEE; mobile phone. Thus we chose a more reliable methodology for lifespan estimation called "estimation from the number of discarded commodities for each lifespan" according to Oguchi et al. (2010). We applied this methodology on a large sample of EoL mobile phones from a nationwide collection to ensure representativeness of the sample data. This methodology was used e.g. by Mueller et al. (2007) and Walk (2009).

Probabilistic distribution, which is often used for modelling of product lifespan, is called Weibull distribution and was used in Nordic Council of Ministers (2009), Tasaki et al. (2004), Oguchi et al. (2008) and Walk (2009). Brief description of the estimation method is shown in Fig. 2.

Analysed mobile phones were collected in the beginning of the year 2008 throughout the Czech Republic within a national collection campaign conducted by mobile operator T-Mobile and WEEE take-back system REMA System. Motivation in this campaign was a voucher for 200 CZK (approximately 8 EUR), which could have been used as a discount on telecommunication services (T-Mobile Czech Republic, 2011). EoL mobile phones were collected in operator's shops, which made the collection available for the public. Collection was supported by an extensive promotion. With 32,566 collected mobile phones, it remains the most successful campaign in the Czech Republic (personal communication with REMA System).

The information about brand was available for all 32,566 collected phones, whereas the year of manufacture was possible to identify only for 28,665 units (88%). Information about the year of manufacture were found on the internet, e.g. on Mobilesdata.com (2010).

To estimate the change of mobile phone lifespan distribution in the time, sampling of 3362 mobile phones was provided in the year 2010. Analysed mobile phones were a sample of 12,000 EoL mobile phones collected in the year 2010 within a national project run by the Czech WEEE take-back system REMA System, together with 15 Czech zoological gardens. Motivation for the public was protection of endangered species in situ, supported by donation of approximately 0.4 EUR given per every collected EoL mobile phone. Mobile phones were collected directly in zoological gardens, which also promoted this campaign (personal communication with REMA System).

For the purpose of this paper, data on import and export of mobile phones are necessary. Data for the years 1996–2010, were obtained from Intrastat, an online database of foreign trade of the Czech Statistical Office (CSO, 2010b). For the years 1991–1995 a simple estimation was done. Future sales were estimated by approximation of partial sums method data by logistic curve. Similar method has been used in Seger (1988). Accuracy of the data on number of mobile phones placed on the market depends on accuracy of its evidence called Intrastat. Intrastat database does not include data on individual trading operations carried out by

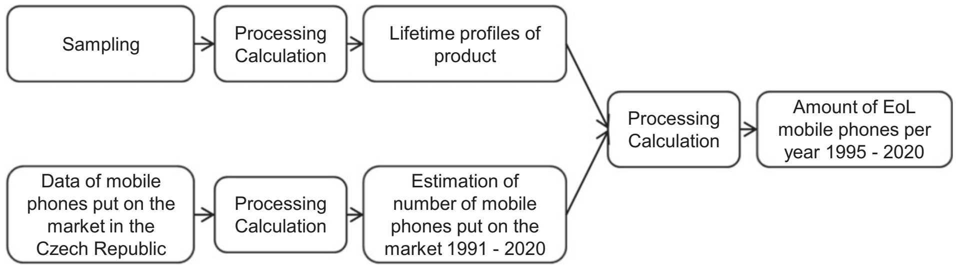

Fig. 2. Scheme of the estimation method used.

persons, who are not registered for value added tax. Furthermore, reports on amount of imported units below the applicable thresholds of 8 million CZK a year are not under reporting duty for Intrastat. This trade is included in statistics by using mathematical and statistical imputation. Another inaccuracy can be caused by illegal imports. However, we consider all these amounts negligible.

The basic formula for estimation of generation of EoL mobile phones in units can be defined:

$$G_t = \sum_i [(P_{t-i} - E_{t-i} + I_{t-i}) \cdot p_t(i)] \tag{1}$$

$$P_t = F(t)_2 - F(t)_1 \tag{2}$$

where: G_t – generation of EoL mobile phones in the year t; P_t – domestic production in the year t; E_t – Export in the year t; I_t – Import in the year t; $p_t(i)$ – probability of EoL mobile phones arising in individual year i of product lifespan in the year t; i – lifespan of i years of mobile phone; $F(t)$ – Weibull cumulative distribution function; Cumulative distribution function of Weibull distribution $F(t)$, which is used for calculation of mobile phone lifespan, is defined as:

$$F(t) = 1 - \exp[-((t-\gamma)/\alpha)^{\beta}] \tag{3}$$

where α is scale parameter (or characteristic Weibull lifespan), β is shape parameter and γ is location parameter. In our case $\gamma = 0$, therefore:

$$F(t) = 1 - \exp[-(t/\alpha)^{\beta}] \tag{4}$$

For the two-parameter case, the mean value Av is:

$$Av = \alpha \cdot \Gamma(1 + 1/\beta) \tag{5}$$

where Γ is gamma function

3.1. Estimation of parameters of Weibull distribution

To estimate the Weibull distribution parameters, several methods like maximum likelihood estimation method, method of moments and least-squares estimation method (LSE) are used. We choose LSE method, because it is very simple and commonly used by practitioners (Zhang et al., 2006). Moreover, it is easily applicable in a spreadsheet calculator.

Weibull cumulative distribution function (4) was transformed into the shape of formula of straight line: $y = k \cdot x + q$

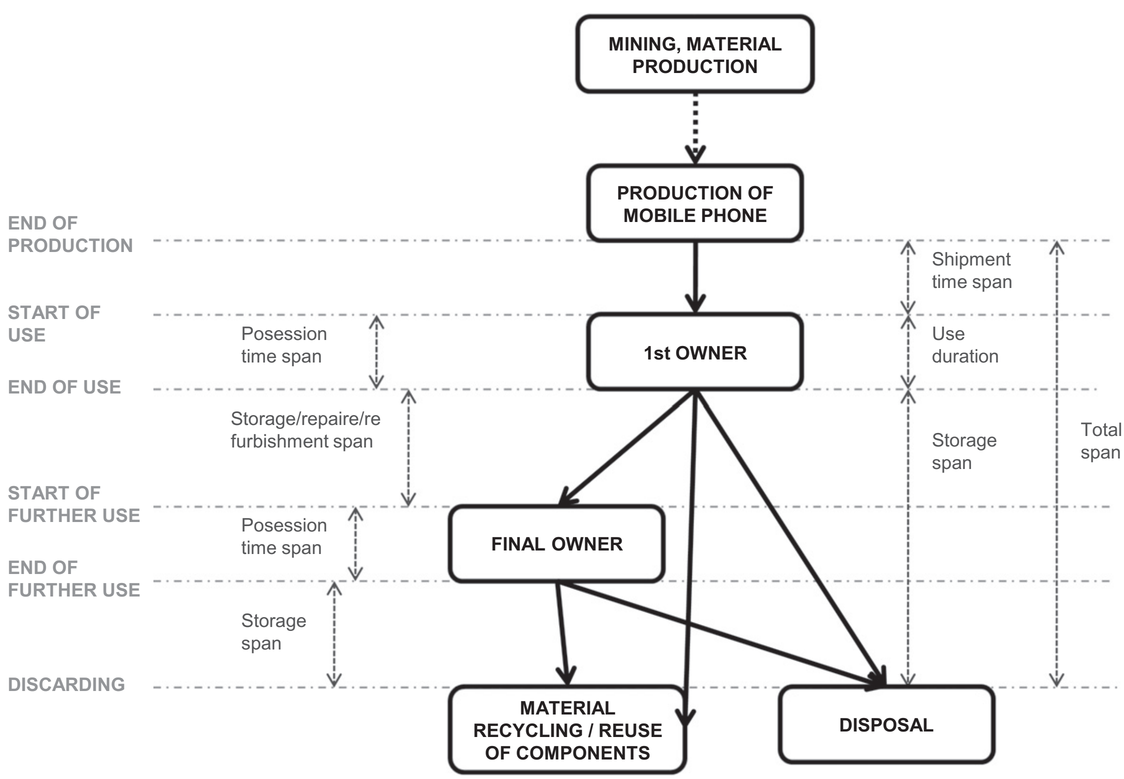

Fig. 3. Scheme of lifespan of a mobile phone (modified from Murakami et al., 2010).

Table 3
Brand proportion of collected EoL mobile phones in the year 2008.

Brand of mobile phone	Units	%
Nokia	8324	25.6
Siemens	8147	25.0
Alcatel	5681	17.4
Motorola	3032	9.3
Ericsson	2002	6.1
Philips	1471	4.5
Sagem	670	2.1
Bosch	688	2.1
Sony	606	1.9
Sonny-Ericsson	608	1.9
Panasonic	595	1.8
Samsung	357	1.1
LG	208	0.6
Mitshubishi	177	0.5
Total	32,566	100.0

$$F(t) = 1 - \exp[-((t-\gamma)/\alpha)^{\beta}] \quad (6)$$

$$\ln(1 - F(t)) = -(t/\alpha)\beta \quad (7)$$

$$\ln(-\ln(1 - F(t))) = \beta \cdot \ln t - \beta \cdot \ln \alpha \quad (8)$$

Substitution is implemented:

$$y = \ln(-\ln(1 - F(t))) \quad (9)$$

$$k \cdot x = \beta \cdot \ln t \quad (10)$$

$$q = -\beta \cdot \ln \alpha \quad (11)$$

Several formulas have been proposed for the best estimation of empirical cumulative distribution function F_i. For complete data, the median rank approximation proposed by Bernard and Bosi-Levenbach (1953), commonly called Bernard's estimator, is widely used. Its formula is

$$F_i(m) = (n_i - 0.3)/(n + 0.4) \quad (12)$$

In our case n_i is ordered number of the age of mobile phone and n is total number of mobile phones, for which the age was determined. The y_i value is calculated in a formula (9). Plotting ln t_i on y_i we get points and between them interpose straight line using the method of LSE. Obtained straight line formula is used for an estimation of two-parameter Weibull distribution. The straight line formula is compared with formulas (10) and (11). Gradient of a straight line k corresponds with a value of a shape parameter β, scale parameter α is calculated in the formulas (13) and (14):

$$\ln \alpha = -q/\beta \quad (13)$$

$$\alpha = \exp(-q/\beta) \quad (14)$$

3.2. Definition of mobile phones lifespan

Since delay method is dependent on the product lifespan, it is crucial to set an exact definition of this term. Terminology of the term lifespan in literature sources is not unified. Likewise, informa-

Table 4
Data for calculation of the inputs for Weibull probability plot.

t_i	Frequency	n_i	$F(t) = n_i/n$	$F(t) = (n_i - 0.3)/(n - 0.4)$	Ln (−Ln (1 − $F(t)$))	Ln ($t_i - \gamma$)
1	11	11	0.0004	0.0004	−7.8930	0.0000
2	5	16	0.0006	0.0005	−7.5095	0.6931
3	137	153	0.0053	0.0053	−5.2323	1.0986
4	1389	1542	0.0538	0.0538	−2.8953	1.3863
5	2143	3685	0.1286	0.1285	−1.9835	1.6094
6	3447	7132	0.2488	0.2488	−1.2515	1.7918
7	3132	10,264	0.3581	0.3581	−0.8136	1.9459
8	2870	13,134	0.4582	0.4582	−0.4897	2.0794
9	5446	18,580	0.6482	0.6482	0.0436	2.1972
10	3216	21,796	0.7604	0.7603	0.3567	2.3026
11	4400	26,196	0.9139	0.9138	0.8967	2.3979
12	1282	27,478	0.9586	0.9586	1.1580	2.4849
13	684	28,162	0.9825	0.9824	1.3966	2.5649
14	503	28,665	1.0000	1.0000	2.3628	2.6391
15	0	28,665	1.0000	1.0000	2.3628	2.7081
n	28,665					

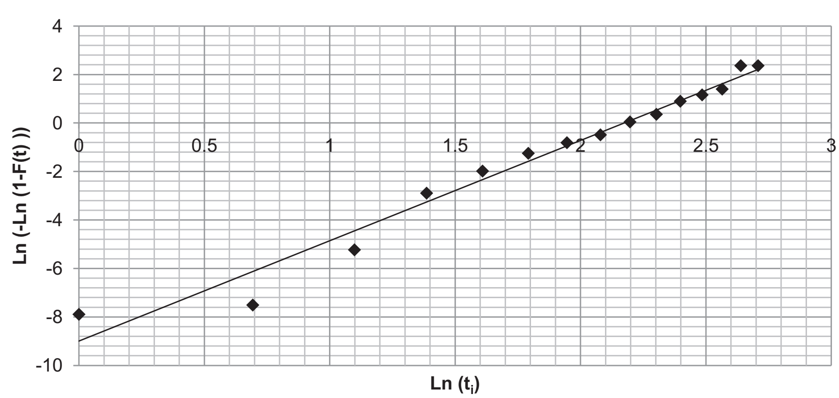

Fig. 4. Weibull probability plot.

tion about lifespan of mobile phones varies significantly. Average lifespan of mobile phone is estimated 2.5 years (Nokia, 2005), 2.0 years (Mc Laren et al., 1999), 4.0 years (Crowe et al., 2003), 4.3 years including storage (Oguchi et al., 2008) or in case of Nigeria 7.0 years (Osibanjo and Nnorom, 2008). Other studies mention 1.5 years (Most, 2003) or 2.0 years (Gaidajis et al., 2010). According to Marcussen (2002), average economic lifespan of mobile phone is 3.0 years for China, 2.3 years for US and Western Europe and 1.7 years for Japan.

For the purpose of this paper, we considered "total lifespan" as the most appropriate lifespan-related period for reliable estimation, as distribution of total lifespan can be obtained from a survey at recycling and waste treatment facility (Oguchi et al., 2010). According to National Institute for Environmental Studies (2011) total lifespan denotes the duration of the period, in which the goods exist in our society in their original form, regardless of whether the goods still function. Fig. 3 shows the life cycle of mobile phones with various terms used to describe their lifespan.

3.3. Hypothesis and assumption

We assume that the lifespan function is constant for all estimated years and equals to model lifespan based on empirical data gained by analyses of mobile phones collected in the year 2008. According to Oguchi et al. (2010), lifespan distribution obtained by the "estimation from the number of discarded commodities for each lifespan" method can be biased by the exclusion of data on mobile phones exported or illegally dumped after being discarded. Nevertheless, in case of our research, we consider this bias negligible. Within the scope of this article, the lifespan analysis was conducted for business to consumer (B2C) mobile phones and we assume that lifespan function is similar for B2C and for business to business (B2B) mobile phones. According to estimations of TNS Aisa (Vaněček, 2011), the ratio of B2C mobile phones to B2B is 70% to 30%. From interviews with importers and producers, it was found out that there is no production of mobile phones in the Czech Republic, hence all mobile phones are imported or imported and afterwards exported.

4. Results and discussion

4.1. Sampling results and life span analysis

Analysed EoL mobile phones were sorted according to the brands and types in order to gain the data on the year of production. Proportion according to brands is depicted in Table 3.

The LSE method using spreadsheet calculator was used to determine model parameters using Weibull probability plot as shown in Table 4 and Fig. 4. Resulting value was 4.14 for shape parameter. Characteristic Weibull lifespan for an EoL mobile phone for the year 2008 was estimated to be 8.79 years. Average lifespan (mean value) was estimated to be 7.99 years. This value is much higher in comparison with other results for mobile phones published in aforementioned literature sources (see Section 3.2). To show, that there are no significant fitting errors caused by the use of LSE method, scatter graph with both raw data and fitted data is provided in Fig. 5.

Comparison of lifespan distribution of mobile phones estimated within this study and lifespan distribution of mobile phones in Norway estimated by Nordic Council of Ministers (2009) is presented in Fig. 6. The figure shows a significant difference between the two lifespans, which reflects the fact that Norway is in the long term one of the countries with highest WEEE collection rate per capita. Application of Norwegian mobile phone lifespan in our estimation would result to increase of EoL mobile phones generation by 73% in the year 2010 in the Czech Republic.

Since average lifespan of mobile phone in the Czech Republic seems to be significantly longer than in other countries, it is necessary to analyse this situation further. In the year 2008, a broad survey focused on consumers and their behaviour towards WEEE was conducted (Markent, 2008). The results of 725 answers to the question "How often do you buy a mobile phone?" show that new phones are bought once a year by 5% Czechs, once per 2–5 years by 73%, once per 6–10 years by 21% and less often by 1% of Czechs. From these data it is possible to estimate cumulative distribution function using Newton–Raphson approach as is shown in Nordic Council of Ministers (2009). In our case, the average lifespan (mean value) of mobile phones is 7.99 years, average usage time 3.63 years. As shown in Fig. 7, average storage or reuse time in the year 2008 was 4.35 years, which explains the long "total lifespan" of mobile phones.

4.2. Estimation of EoL mobile phones generation

Results of estimation of EoL mobile phones generation in recent and future years are summarized in Fig. 8. For a comparison, this figure also includes an option, which counts with approximately twice shorter lifespan estimation, which is currently estimated for Norway (Nordic Council of Ministers, 2009). The results show that while in the years 1990–2000 about 45 thousand EoL mobile phones were generated, in the years 2000–2010 this amount grew to 6.5 million and it can be estimated that the amount will grow further up to 26.3 million of EoL mobile phones in years 2010–2020.

As we tried to compare our results with estimations in other countries, we found out that there are often no official statistics on quantities of mobile phone disposed. Moreover, available data are not comparable due to difference in approach towards life span

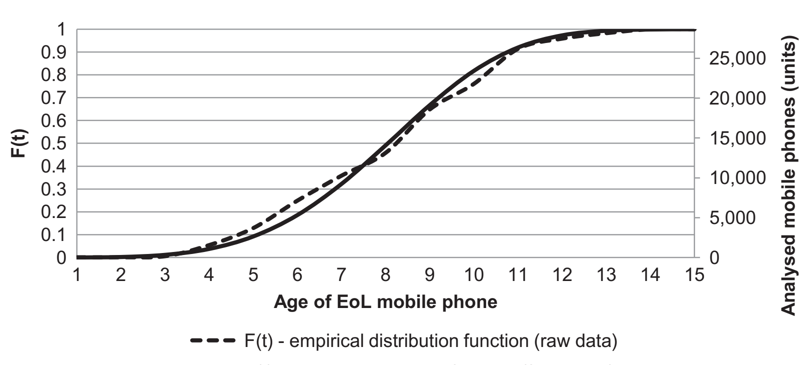

Fig. 5. Comparison of raw and fitted data.

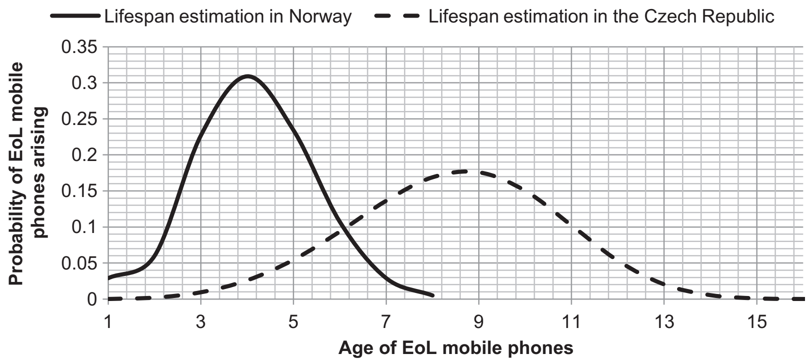

Fig. 6. Comparison of lifespan distribution of mobile phones in the Czech Republic and Norway.

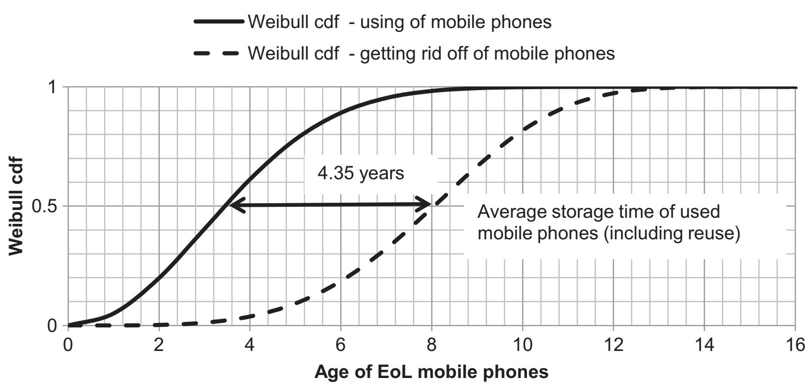

Fig. 7. Estimation of average storage time of used mobile phones in the Czech Republic (including reuse).

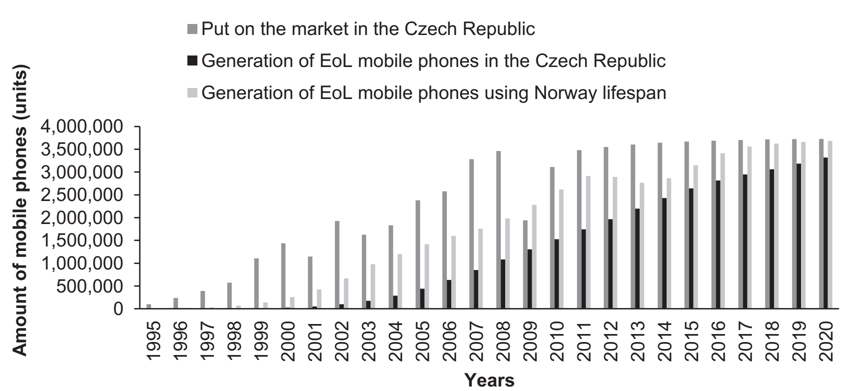

Fig. 8. Generation of EoL mobile phones ("units") in the years 1995–2020 in the Czech Republic.

definition. For example, amounts of EoL phones stated by Fishbein (2002) are significantly higher and probably overestimated on account to use of possession lifespan for the calculation. Estimation for different countries are summarised in Table 5.

4.3. Sensitivity analysis of estimation and uncertainties

One of the possible inaccuracies, which can influence estimation of EoL mobile phones generation, could be caused by including of shipment time span into the total lifespan (see Fig. 3). We assume shipment time as time interval of maximum 1 year, between production and actual placement on the market of a mobile phone. If we shifted empirical data by one year ahead (assuming that the

Table 5
Comparison of data on EoL mobile phone generation in various countries.

Country	Year	EoL mobile phones estimation (milion units)	References
Czech Republic	2008	1.3	Our results
Korea	2007	15.9	Jang and Kim, 2010
China	2008	77.0	Yu et al., 2010
United Kingdom	2008	18.0	Ongondo and Williams, 2011
USA	2005	130.0	Fishbein, 2002
Japan	2003	45.0	Oguchi et al., 2008

mobile phones had been produced in the year t and sold in the year $t+1$), then, parameters of the 3 – parametric Weibull distribution would be $\gamma = 1$, $\alpha = 7.59$ and $\beta = 3.66$. Sensitivity analysis showed that this time shift does not influence estimated amount of generated EoL mobile phones significantly, as individual estimations for the years 2000–2020 vary by maximum 4% in comparison with baseline estimation.

Another uncertainty is the assumption that the estimated lifespan distribution is constant for all the years. To estimate the change of mobile phone lifespan distribution in the time we compared estimated lifespan distribution for the year 2008 and 2010. For the year 2010, parameters of 2 – parametric Weibull distribution were estimated $\alpha = 9.66$ and $\beta = 4.59$. Mean value of lifespan was 8.82 years in the year 2010. This result shows surprising fact that the lifespan of mobile phones lengthened by 0.83 years between the years 2008 and 2010. We assume that this fact can be explained by prolonged storage span of EoL mobile phones at households. This can be caused by several reasons, which we generally call "treasure effect", mainly by the fact that consumers keep their phones as spare or they consider EoL mobile phones valuable (e.g. information stored in mobile phones) (Ongondo and Williams, 2011). However, further research in this field is needed. If we estimate EoL mobile phone generation in the year 2010 using lifespan distribution based on data from the year 2010 instead of lifespan data from the year 2008, we get a difference of −17.8%.

Further uncertainty results from the fast technology change in ICT technologies. One of the changes is expansion of the market for smart phones, which can be considered as mobile phones (Chancerel, 2010). Global sales of smart phones were up 74% year-on-year and accounted for 25% of overall sales in the second quarter of 2011, up from 17% in the second quarter of 2010 (Gartner, 2012). The estimation of future sales of mobile phones presented in this article includes this change, as we did not distinguish between smart phones and mobile phones. Other changes in ICT sector were not considered in this paper.

4.4. European collection targets and resources conservation

In the year 2010, 3.1 million mobile phones were put on the market in the Czech Republic (CSO, 2010b). We estimate that in the same year approximately 1.5 million EoL mobile phones were generated. Even though this amount of mobile phones was available for recycling, based on the data from personal communication with WEEE collection take-back systems, we estimate that in the year 2010, only 50–100 thousand units of EoL mobile phones were actually collected. Thus collection rate of EoL mobile phones produced in 2010 was about 3.4–6.7% and collection rate of amount put on the market was 1.6–3.2%. Such low collection rates denote need for setting up legislatively binding collection targets specific for mobile phones and other small EEE.

From resources conservation point of view, such low collection rates mean considerable loss of valuable materials. If we suppose that estimated EoL mobile phones generation in the years 2010–2020 in the Czech Republic can be considered to be EU average (2.55 EoL mobile phones/inhabitant/10 years) and apply this assessment on the number of inhabitants in the EU, we get gigantic numbers. According to the estimate, 1.3 billion of EoL mobile phones would be available for recycling in the EU within the years 2010–2020. If we assume that 1 mobile phone contains 250 mg of Ag and 24 mg of Au (Hagelüken and Corti, 2010), this amount would contain approximately 31 tonnes of gold and 325 tonnes of silver. Note that these figures are only indicative, but the order of magnitude is correct. At the same time, EU is highly dependent on imports of many raw materials which are increasingly affected by growing demand from emerging economies and by an increasing number of national policy measures that disrupt the normal operation of global markets (EC, 2010).

5. Conclusion

The aim of this article was to analyse mobile phones lifespan on the case of the Czech Republic and to estimate EoL mobile phones generation in the Czech Republic in the years 1995–2020. There is currently no other study that would quantitatively assess the total lifespan and generation of EoL mobile phones in the Czech Republic, even though mobile phones use and their disposal in the Czech Republic is extensive. This article presents data that fills the gap in the knowledge and help to enhance understanding in this field.

We conducted the lifespan calculation for the year 2008 based on sampling of 32,566 EoL mobile phones, which is unique to the Czech Republic. Average lifespan (mean value) was estimated to be 7.99 years. Average usage time of mobile phones was estimated 3.63 years, average storage or reuse time was 4.35 years. To estimate the change of mobile phone lifespan distribution in the time we compared estimated lifespan distribution for the year 2008 and 2010. The lifespan calculation for the year 2010 was based on sampling of 3362 EoL mobile phones. Mean value of lifespan was 8.82 years, shows surprising fact that the lifespan of mobile phones lengthened by 0.83 years between the years 2008 and 2010. However the change of total life span and the role of storage shall be further researched.

The results of estimation of EoL mobile phones generation in the Czech Republic show, that while in the years 1990–2000 about 45 thousand EoL mobile phones were generated, in the years 2000–2010 this amount grew to 6.5 million. We estimate that the amount will grow further up to 26.3 million of EoL mobile phones in years 2010–2020. The results of future EoL mobile phones generation estimation in the Czech Republic shall be taken with precautions mainly for the reason that change of total lifespan of EoL mobile phones in time and market and technological development can be expected.

Results of this study clearly show increasing trend of EoL mobile phones generation. Due to this fact and relatively long storage time of over 4 years, huge amount of material escapes from recycling, by being stored in society. Our findings underscore the need for specific collection targets for s-WEEE such as EoL mobile phones. This is even more important for the Czech Republic given that it has a very high penetration of mobile phones per inhabitant.

6. Recommendation

To set a working system of collection of EoL mobile phones, it will be necessary to set new and effective collection targets. Moreover, these targets shall be supported by an optimal mix of consumer incentives and motivations.

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References

BBC, 2002. A mobile is not just for Christmas. <http://news.bbc.co.uk/2/hi/technology/2603589.stm> (accessed 04.11.11.).

Bernard, A., Bosi-Levenbach, E.C., 1953. The plotting of observations on probability paper. Stat Neerlandica 7, 163–173.

Chancerel, P., 2010. Substance flow analysis of the recycling of small WEEE Institut für Technischen Umweltschutz Berlin, Dissertation thesis, p. 161.

Chung, S.S., Lau, K.Y., Zhang, C., 2010. Generation of and control measures for, e-waste in Hong Kong. Waste Manag. 31, 544–554.

Crowe, M., Elser, A., Göpfert, B., Mertins, L., Meyer, T., Schmid, J., Spillner, A., Ströbel, R., 2003. Waste from electrical and electronic equipment (WEEE) – quantities, dangerous substances and treatment methods. European Environment Agency, Copenhagen.

Czech Statistical Office (CSO), 2010a. Equipment of Households by a Fixed Phone and Mobile Phone <http://www.czso.cz/csu/redakce.nsf/i/1_vybavenost_domacnosti_pevnou_telefonni_linkou_a_mobilnim_telefonem> (accessed 04.11.11.) (in Czech).

Czech Statistical Office (CSO), 2010b. Online Database for Statistics of Foreign Trade. <http://apl.czso.cz/pll/stazo/STAZO.STAZO> (accessed 04.11.11) (in Czech).

Directorate General Communication, 2010. E-Communications Household Survey Summary – TNS Opinion & Social, Survey, Eurobarometer. Brussels <http://ec.europa.eu/public_opinion/archives/ebs/ebs_335_sum_en.pdf> (accessed 04.11.11).

Dwivedy, M., Mittal, R.K., 2010. Future trends in computer waste generation in India. Waste Manage. 30, 2265–2277.

European Commission (EC), 2010. Critical raw materials for the EU. European Commission. <http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report_en.pdf> (accessed 04.11.11).

European Parliament, 2012. <http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+REPORT+A7-2011-0334+0+DOC+XML+V0//EN#> (accessed 10.02.12).

European Commission-RoHS Directive, 2003. Directive 2002/95/EC of the European Parliament and of the Council on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment. Brussels, Belgium, European Commission.

European Commission-WEEE Directive, 2003. Directive 2002/96/EC of the European Parliament and of the Council on Waste Electrical and Electronic Equipment (WEEE). Brussels, Belgium, European Commission.

Feszty, K., Murchison, C., Baird, J., Jamnejad, G., 2003. Assessment of the quantities of waste electrical and electronic equipment (WEEE) in Scotland. Waste Manag. Res. 21, 207–217.

Fishbein, B.K., 2002. Waste in the Wireless World: the challenge of cell phones. INFORM, USA. http://www.informinc.org/reportpdfs/wp/WasteintheWirelessWorld.pdf (accessed 04.11.11).

Gaidajis, G., Angelakoglou, K., Aktsoglou, D., 2010. E-waste: environmental problems and current management. J. Eng. Sci. Technol. Rev. 3, 193–199.

Gartner, 2012. Gartner Says Sales of Mobile Devices in Second Quarter of 2011 Grew 16.5 Percent Year-on-Year; Smartphone Sales Grew 74 Percent. <http://www.gartner.com/it/page.jsp?id=1764714> (accessed 15.02.12).

Hagelüken, C., Corti, C., 2010. Recycling of gold from electronics: cost effective use through 'Design for Recycling'. Gold Bull. 43 (3), 209–220.

Huisman, J., 2004. QWERTY and Eco-Efficiency analysis on cellular phone treatment in Sweden. The eco-efficiency of the direct smelter route versus mandatory disassembly of Printed Circuit Boards. Stockholm. <http://basel.int/industry/qwerty-sweeden.pdf> (accessed 04.11.11).

Huisman, J., Magalini, F., Kuehr, R., Maurer, C., Ogilvie, S., Poll, J., Delgado, C., Artim, E., Szlezak, J., Stevels, A., 2007. 2008 Review of directive 2002/96 on waste electrical and electronic equipment (WEEE) final report. United Nations University, Bonn.

International Telecommunication Union (ITU), 2011a. Key 2005–2011 ICT data, by geographic regions and by level of development. <http://www.itu.int/ITU-D/ict/statistics/at_glance/KeyTelecom.html> (accessed 29.01.12).

International Telecommunication Union (ITU), 2011b Mobile cellular subscriptions Key 2000-2010 country data (Excel format) – Mobile cellular subscriptions http://www.itu.int/ITU-D/ict/statistics/ (accessed 02.02.12).

Jang, Y.C., Kim, M., 2010. Management of used & end-of-life mobile phones in Korea: a review. Resour. Conserv. Recycling 55, 11–19.

Kang, H.Y., Schoenung, J.M., 2006. Estimation of future outflows and infrastructure needed to recycle personal computer systems in California. J. Hazard. Mater. 137, 1165–1174.

Lin, C., 2008. A model using home appliance ownership data to evaluate recycling policy performance. Resour. Conserv. Recycling 52, 1328–1332.

Marcussen, C.H., 2002. Mobile Phones, WAP and the Internet – The European Market and Usage Rates in a Global Perspective 2000-2003. <http://www.crt.dk/uk/staff/chm/wap/2000.pdf> (accessed 14.02.12).

Markent, 2008. Způsoby nakládání s nefunkčním elektrozařízením – domácnosti v ČR. Asekol, Elektrowin, Ekolamp. Praha. (Ways of treatment of non-functional electrical and electronic equipment – Households in the Czech Republic). (in Czech).

Mc Laren, J., Wright, L., Parkinson, S., Jackson, T., 1999. A dynamic life-cycle energy model of mobile phone take-back and recycling. J. Ind. Ecol. 3, 77–91.

Mobilesdata.com, 2010. <http://www.mobilesdata.com/> (accessed 04.11.11).

Most, E., 2003. Calling All Cell Phones: Collection, Reuse, and Recycling Programs in the US. INFORM. New York, USA. <http://www.informinc.org/calling_cellphones.php> (accessed 04.11.11).

Mueller, D., Cao, B.J., Kongar, E., Altonji, M., Weiner, P-H., Greadel, T.E. 2007. Service lifetimes of mineral end use. U.S. Geological Survey, Minerals Resources External Research Program Award Number: 06HQGR0174. <http://minerals. usgs.gov/mrerp/reports/Mueller-06HQGR0174.pdf> (accessed 16.02.2012).

Murakami, S., Oguchi, M., Tasaki, T., Daigo, I., Hashimoto, S., 2010. Lifespan of commodities, part I: the creation of a database and its review. J. Ind. Ecol. 14 (4), 598–612.

National Institute for Environmental Studies, 2011. Lifespan database for Vehicles, Equipment, and Structures: LiVES. <http://www.nies.go.jp/lifespan/index-e.html> (accessed 04.11.11).

Nokia, 2005. Life cycle environmental issues of mobile phones. Stage I Final Report. Espoo. <http://ec.europa.eu/environment/ipp/pdf/nokia_mobile_05_04.pdf> (accessed 04.11.11).

Nordic Council of Ministers, 2009. Method to measure the amount of WEEE generated. Nordic Council of Ministers. <http://www.norden.org/en/publications/publications/2009-548> (accessed 04.11.11).

Oguchi, M., Kameya, T., Yagi, S., Urano, K., 2008. Product flow analysis of various consumer durables in Japan. Resour. Conserv. Recycling 3, 463–480.

Oguchi, M., Murakami, S., Tasaki, T., Daigo, I., Hashimoto, S., 2010. Lifespan of commodities, part II: methodologies for estimating lifespan distribution of commodities. J. Ind. Ecol. 14 (4), 613–626.

Ongondo, F.O., Williams, I.D., 2011. Greening academia: use and disposal of mobile phones among university students. Waste Manag. 31, 1617–1634.

Osibanjo, O., Nnorom, I.C., 2008. Material flows of mobile phones and accessories in Nigeria: environmental implications and sound end-of-life management options. Environ. Impact Assess. Rev. 28 (2–3), 198–213.

Royal Institution of Chartered Surveyors, 2011. RICS draft information paper – Rare Earth Metals. <https://consultations.rics.org/consult.ti/_rem/viewCompoundDoc?docid=921940> (accessed 04.11.11).

Seger, J., 1988. Statistické metody pro ekonomy průmyslu. (Statistical methods for industrial economists). Státní nakladatelství technické literatury Alfa, Praha. 545 p. (in Czech).

Steubing, B., Boni, H., Schluep, M., Silva, U., Ludwig, C., 2010. Assessing computer waste generation in Chile using material flow analysis. Waste Manag. 30, 473–482.

Tasaki, T., Takasuga, T., Osako, M., Sakai, S., 2004. Substance flow analysis of brominated flame retardants and related compounds in waste TV sets in Japan. Waste Manag. 24 (6), 571–580.

T-Mobile Czech Republic, 2011. <http://storage.prosvetkolemnas.cz/contentresources/Den-mobilni-etikety-na-podporu-recyklace-14-19.pdf> (accessed 06.02.12).

UNEP, 2009. MPPI: Guideline on the awareness raising-design considerations. <http://archive.basel.int/industry/mppiwp/guid-info/guiddesign.pdf> (accessed 14.03.12).

UNU, 2007. Recycling Of Europe's Electronic Waste Needs Improvement, UN Report Urges, Science Daily. <http://www.sciencedaily.com/releases/2007/11/071115113338.htm> (accessed 04.11.11).

Van der Voet, E., Kleijn, R., Huele, R., Ishikawa, M., Verkuijlen, E., 2002. Predicting future emissions based on characteristics of stocks. Ecol. Econ. 41, 223–234.

Vaněček, P., 2011. TNS Aisa. Personal Communication.

Walk, W., 2009. Forecasting quantities of disused household CRT appliances – a regional case study approach and its application to Baden-Wurttemberg. Waste Manag. 29, 945–951.

Yang, Y., Williams, E., 2009. Logistic model-based forecast of sales and generation of obsolate computers in the U.S. Technol. Forecasting Soc. Change 76, 1105–1114.

Yoshida, A., Tasaki, T., Terazono, A., 2009. Material flow analysis of used personal computers in Japan. Waste Manag. 29, 1602–1614.

Yu, J., Williams, E., Ju, M., 2010. Analysis of material and energy consumption of mobile phones in China. Energy Policy 38, 4135–4141.

Zhang, L.F., Xie, M., Tang, L.C., 2006. Bias correction for the least squares estimator of Weibull shape parameter with complete and censored data. Reliability Eng. Syst. Saf. 91, 930–939.

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Selective recovery of gold from waste mobile phone PCBs by hydrometallurgical process

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ABSTRACT

The leaching of gold from the scrap mobile phone PCBs by electro-generated chlorine as an oxidant and its recovery by ion exchange process was investigated. The leaching experiments were carried out by employing separate leaching reactor connected with the anode compartment of a Cl_2 gas generator. The leaching of gold increased with increase in temperature and initial concentration of chlorine, and was favorable even at low concentration of acid, whereas copper leaching increased with increase in concentration of acid and decrease in temperature. In a two-stage leaching process, copper was mostly dissolved (97%) in 165 min at 25 °C during the 1st stage leaching in 2.0 mol/L HCl by electro-generated chlorine at a current density of 714 A/m^2 along with a minor recovery of gold (5%). In the 2nd stage gold was mostly leached out (93% recovery, ~67 mg/L) from the residue of the 1st stage by the electro-generated chlorine in 0.1 mol/L HCl. Gold recovery from the leach liquor by ion exchange using Amberlite XAD-7HP resin was found to be 95% with the maximum amount of gold adsorbed as 46.03 mg/g resin. A concentrated gold solution, 6034 mg/L with 99.9% purity was obtained in the ion exchange process.

1. Introduction

Due to rapid economic growth, technological advances and the obsolescence of electronic equipment in the market, the amount of waste mobile phone generation has been growing. It has resulted in hundreds of millions of mobile phones that are taken out of use each year [1]. Besides, increased production of mobile phone would also increase the amount of the waste generation during the manufacturing process. Mobile phone typically consists of a body, printed circuit boards (PCBs), liquid crystal display (LCD), key board, antenna, etc. Among these parts PCBs contain hazardous materials as well as a variety of valuable metals. Therefore, efficient recycling of mobile phone PCBs should be required to secure the metallic resources and to prevent environmental pollution at the same time. Especially, the gold recovery from the used PCBs from the electronic industry has received the most attention because of the presence of a considerable quantity (300–350 mg/kg) of this metal which is generally 100 times higher in concentration than that of the gold ore [2].

Currently, recycling technology for recovery of valuable metals from waste PCBs can be divided into two major steps: (i) upgrading the metal content by mechanical pre-treatment, and (ii) extraction and refining to recover the metals by pyro-/hydro-metallurgical method. In the pyrometallurgical process, a conventional method, it is difficult to recover some metals such as Al, Fe, and rare metals, besides a loss of precious metals. In the last few decades, hydrometallurgical processes have been given considerable attention to recover precious metals as well as rare metals from the waste PCBs [2].

Leaching is the first step in the extraction of gold using hydrometallurgical process. Cyanide leaching [3] has been the predominant method for more than one century due to the selectivity and stability of dicyanoaurate complex in spite of the use of toxic reagents [4]. Several substitutes have recently been proposed as the non-cyanide lixiviants such as thiosulfate [5,6] and aqua regia [7]. Hung et al. [5] reported the leaching of gold from non-populated scraps of PCBs by thiosulfate. The process has the disadvantages such as excessive consumption of reagent with the oxidation of thiosulfate and preferred leaching of copper, the major component of PCBs, high cost of the reagent, and difficulty in recovery process [8]. Aqua regia leaching of gold from computer circuit board scrap [7,9] was also reported to be an effective option, but generation of toxic waste [4] could be a deterrent because of more stringent environmental regulations.

Our research group has been carrying out the leaching of metals from waste PCBs by utilizing electro-generated chlorine [10–12].

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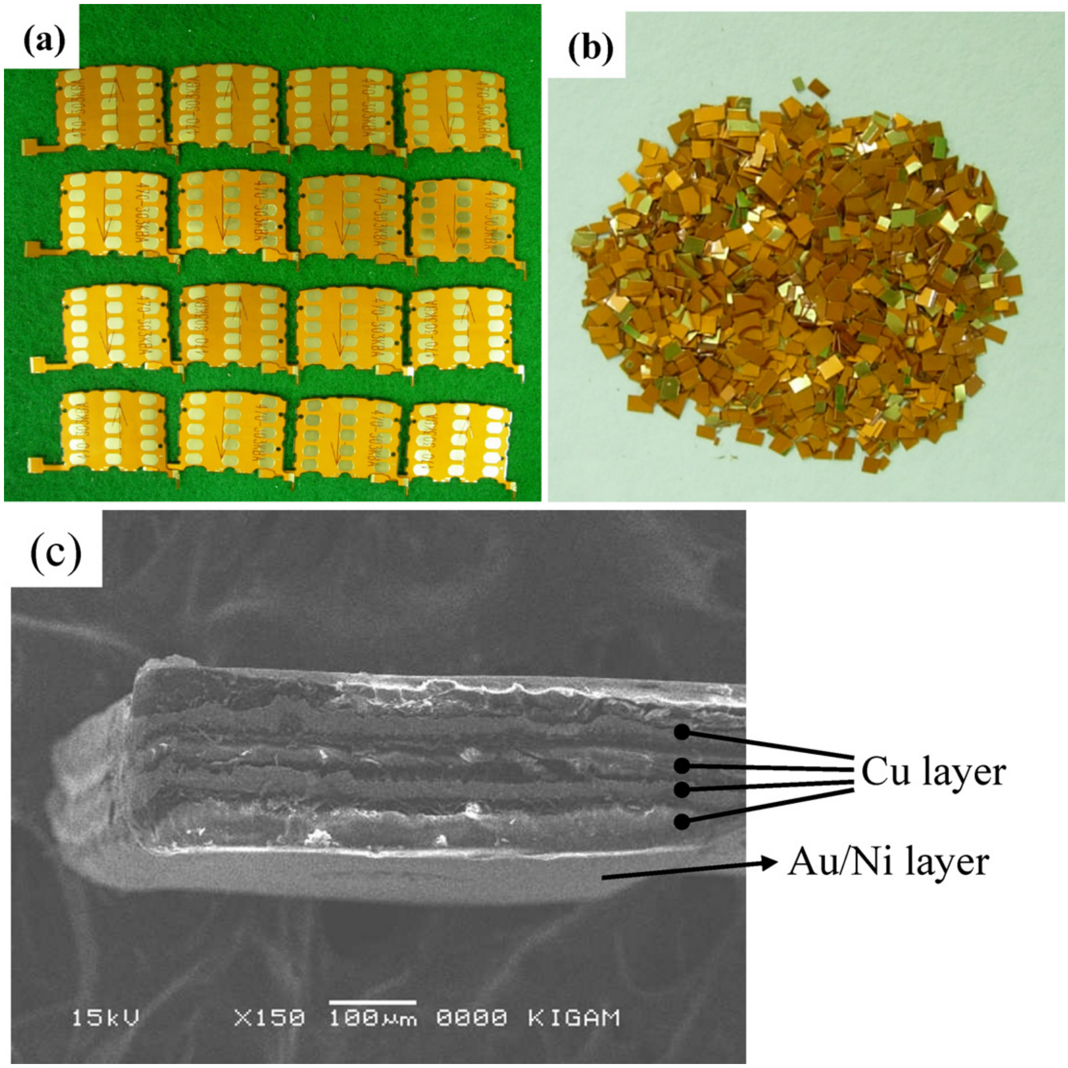

Fig. 1. Scrapped PCBs of mobile phones used for the experiment: (a) as received, (b) after cutting, and (c) SEM image.

The process has the advantage of leaching precious as well as base metals from waste PCBs because of acquiring high oxidation potential. Also, it is considered environment friendly because the electro-generated Cl_2 leaching [10–12] can operate in the closed system and chlorine can be reduced during leaching. The previous studies focused on the leaching mechanism and behavior of copper by electro-generated chlorine using two different reactors: (i) a combined reactor facilitated with simultaneous electro-generation of chlorine and leaching; (ii) a separate leaching reactor connected with anode compartment of a chlorine gas generator [11]. In the combined reactor, the decrease of current efficiency by the oxidation of Cu(I) leached from PCBs to Cu(II) and the low solubility of CuCl were noticed, whereas in the separate reactor no such drawbacks appeared.

This study is focused on the development of a process for selective leaching of gold using the electro-generated chlorine employing the separate reactor and then recovering gold by ion exchange resin. The effect of the process parameters such as acid concentration, temperature, concentration of chlorine, and pulp density has been investigated to understand the mechanism of metal leaching; results are discussed in this paper. Ion exchange process is introduced for separation and enrichment of gold. A more effective process for recovery of gold from waste PCBs could then be established.

2. Experimental

2.1. Leaching by electro-generated chlorine

The non-populated mobile phone PCBs scrap used for the leaching experiment was defective materials obtained from a manufacturer of PCBs (Fig. 1(a)). The chemical composition of the sample is listed in Table 1. The PCBs consist of 66% Cu, 2.30% Ni and 0.045% Au. For leaching experiment, the sample was cut into small pieces of size 2–3 mm unless stated otherwise (Fig. 1(b)). The SEM image of the sample as shown in Fig. 1(c) clearly indicated that copper was inserted between the resin and ceramic materials and gold/nickel was plated on the surface as a thin layer.

Fig. 2 shows the schematic diagram of reactors. The separate reactor consisted of an electrolytic cell for chlorine generation and a separate vessel (reactor) for the metal leaching. The electrolytic

Table 1
Chemical composition of the sample.

	Au	Cu	Ni	Others[a]
wt.%	0.045	66.00	2.30	31.66

[a] Ceramics (Al_2O_3, SiO_2) and resin.

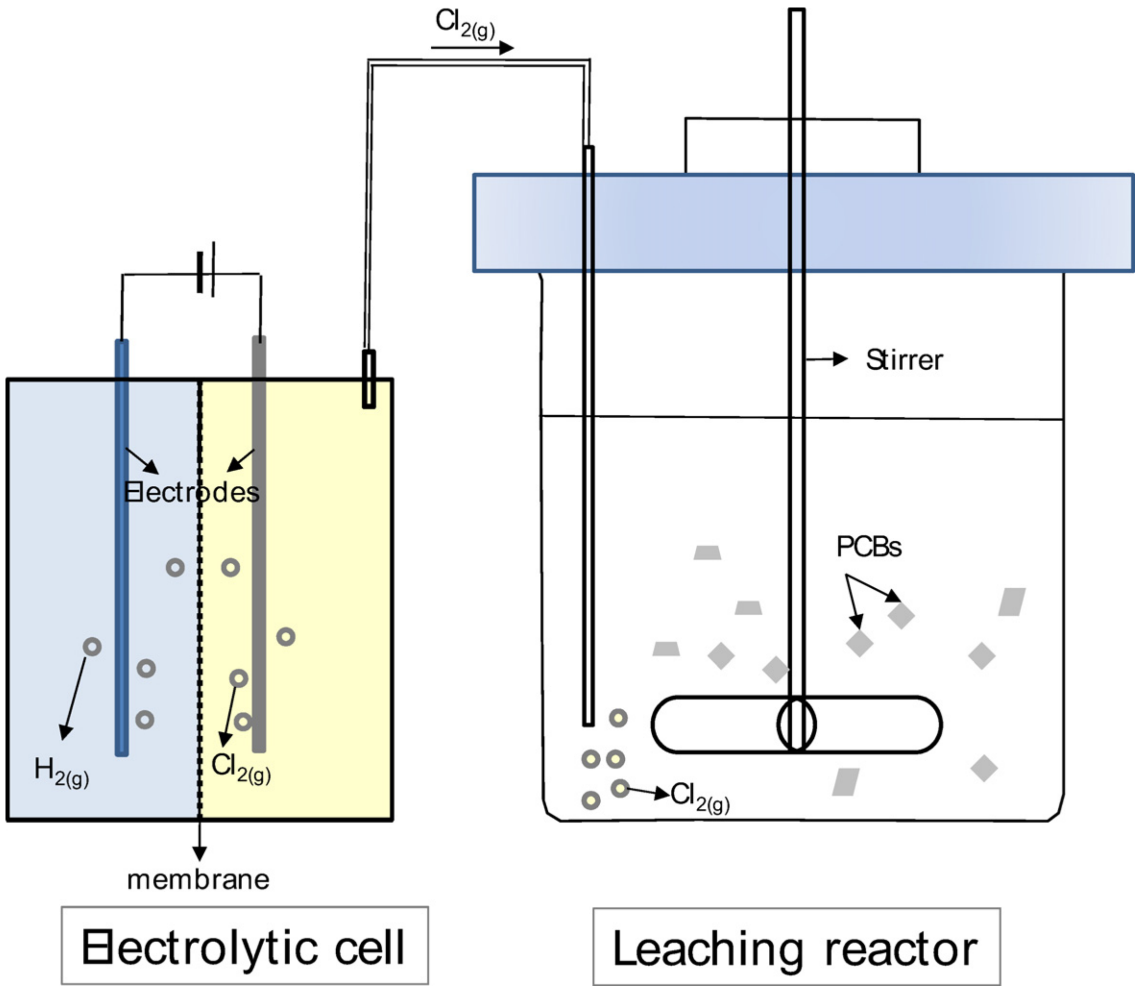

Fig. 2. Leaching apparatus.

cell of acrylic of size 18 cm × 9 cm × 12.5 cm was divided into two compartments with anion exchange membrane (Neosepta AMX, Tokuyama Co.). Two cathodes and anodes were used in these experiments. Both electrodes were made of high purity graphite rods (20 cm (l) × 0.8 cm (d)) with effective area in the solution being 14.0 cm^2/electrode. The anode and cathode compartment of the electrolytic cell was poured 200 mL of 4.0 mol/L, 6.0 mol/L hydrochloric acid solution, respectively and then the anode compartment was saturated with electro-generated chlorine before starting the leaching by supplying constant current. After saturation of anode compartment of the electrolytic cell, 300 mL of hydrochloric acid was poured into the leaching reactor and the solution was heated to the desired temperature by electrically controlled heating bath. A 5.0 g sample except for the experiments of the effect of pulp density was then added for the experiment. The electro-generated chlorine gas from the electrolytic cell was passed to the leaching reactor through a tube. The solution in the leaching reactor was agitated by a PTFE-coated steel impeller at a rotating speed of 500 rpm.

The samples at the predetermined time periods were taken out from the reactors and were analyzed by atomic absorption spectrometer (AAS, AAnalyst 400, PerkinElmer Inc.). The oxidation and reduction potential (ORP, mV vs. Ag/AgCl) in the leach solution was measured and total concentration of oxidants (residual Cl_2(aq) + Cu(II)) was analyzed by the iodide–thiosulfate titration method [13].

2.2. Recovery of gold from leach liquor

2.2.1. Ion exchange of gold by ion exchange resins

In order to investigate the recovery of gold by ion exchange process three resins (Amberlite XAD-7HP, Bonlite BA304, and Purolite A-500) were used. The resins were thoroughly washed with water and dried in oven at 50 °C. A glass column [1 cm (ID) × 25 cm (height)] with a stopcock and a porous disk affixed at the bottom was used in all experiments. The glass column was loaded with 1.0 g (1 bed volume of resin, BV = 4.6 mL) of the resins. After each experiment, the resin filled in the column was washed with a large volume of distilled water and stored in water for the next set of experiment. For each experiment a 5 BV of leach liquor was prepared through 2nd stage leaching by electro-generated chlorine. The solution was passed through the column at a rate of 1.0 mL/min.

Purolite A-500, a macroporous strong base resin was supplied by Purolite Company, whereas Bonlite BA304 (a gel strong base resin) and Amberlite XAD-7HP (a nonionic resin) were obtained from Born Chemical Company and Rohm and Hass, respectively.

2.2.2. Elution in column

The loaded resin was eluted by 0.1 mol/L HCl. The eluted solution was then diluted to 5 vol.% HCl and was analyzed for copper and gold by AAS. The adsorbed gold complex on the column after elution by 0.1 mol/L HCl was eluted again with 1.0 mol/L HCl in acetone and acetone in the eluted solution was evaporated near to dryness.

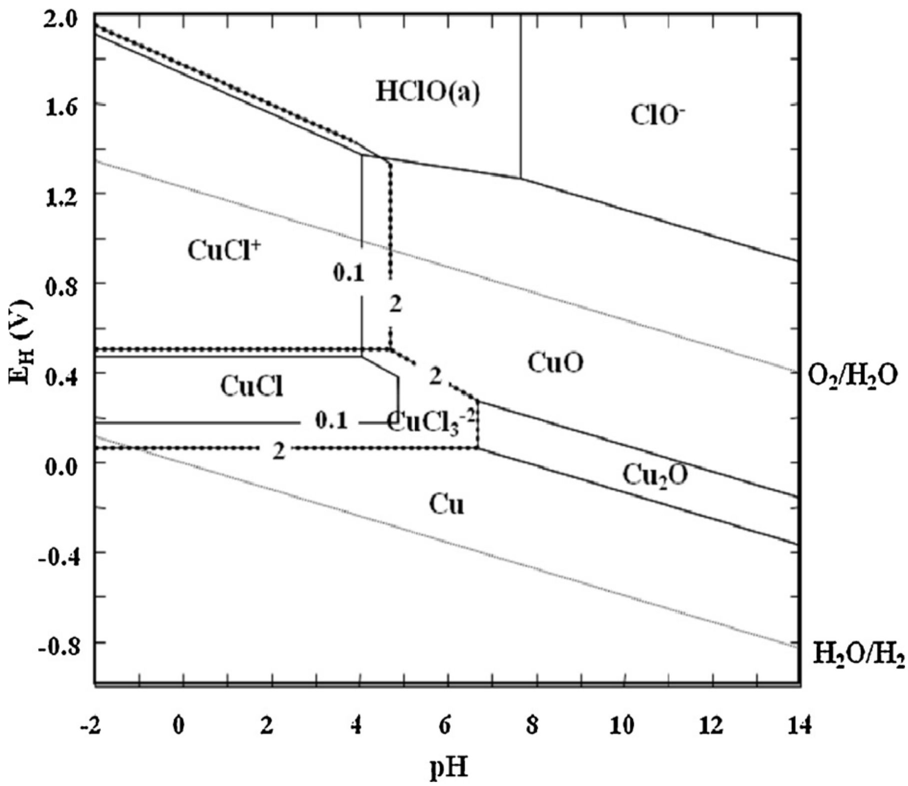

Fig. 3. Cu–Cl–H_2O system at 25 °C ({Cl^-} = 0.1, 2 mol/L, {Cu} = 0.1 mol/L).

The residue was dissolved in 5 vol.% HCl and the final solution was analyzed for copper and gold by AAS.

3. Results and discussion

3.1. Leaching by electro-generated chlorine

Chlorine generation from hydrochloric acid solution can be represented by the following reaction:

$$\text{Anode}: 2Cl^- \leftrightarrows Cl_2(\text{electrodesurface}) + 2e^- \quad E^0 = 1.35\,V_{SHE} \quad (1)$$

The chlorine gas by Eq. (1) dissolves in water as follows (where $\text{Log}\,K_{1-3}$ being the equilibrium constants at 298 K):

$$Cl_{2(g)} \leftrightarrows Cl_{2(aq)} \quad \text{Log}\,K_{1(298)} = -1.21 \quad (2)$$

$$Cl_{2(aq)} + H_2O \leftrightarrows HCl + HOCl \quad \text{Log}\,K_{2(298)} = -3.40 \quad (3)$$

$$Cl_{2(aq)} + Cl^- \leftrightarrows Cl_3^- \quad \text{Log}\,K_{3(298)} = -0.71 \quad (4)$$

The dissolution of gold takes place as [14]:

$$Au + Cl^- + 3/2Cl_{2(aq)} \leftrightarrows AuCl_4^-{}_{(aq)} \quad \Delta G_{298} = -27.04\,\text{kcal/mol} \quad (5)$$

$$Au + 3/2HClO + 3/2H^+ + 5/2Cl^- = AuCl_4^-{}_{(aq)} + 3/2H_2O \quad \Delta G_{298} = -33.29\,\text{kcal/mol} \quad (6)$$

where ΔG is the Gibbs free energy change at 298 K.

The dissolution of copper can be expressed as follows in chloride media [11]:

$$Cu + Cl_{2(aq)} \leftrightarrows Cu^{2+} + 2Cl^- \quad \Delta G_{298} = -46.69\,\text{kcal/mol} \quad (7)$$

$$Cu^{2+} + Cu + 2Cl^- \leftrightarrows 2CuCl \quad \Delta G_{298} = -4.87\,\text{kcal/mol} \quad (8)$$

Thus, thermodynamically the reaction of chlorine with copper (Eq. (7)) is more favorable (lower ΔG_{298} value) than that of gold (Eq. (5)) whereas, the feasibility of reaction of hypochlorous acid (HClO) with gold is higher (Eq. (6)) than the reaction with chlorine (Eq. (5)) under the same condition.

In the presence of chloride, gold and copper dissolve to form Au(III) and Cu(I), Cu(II) chloride complexes, $AuCl_4^-$, $CuCl^+$, $CuCl_3^{2-}$, and CuCl which is evident from the potential (E_h)–pH diagram shown in Figs. 3 and 4 [15]. As the chloride concentration increased from 0.1 to 2.0 mol/L, the stability region of Cu(I) complexes (Fig. 3) and $AuCl_4^-$ (Fig. 4) increased with respect to pH and the redox potential. The E_h–pH diagrams also show that copper as cuprous ion can be leached out at lower potential and higher chloride concentration for complexation and gold needs relatively higher redox conditions and remains in the solution even at low acid concentration.

3.1.1. Effect of acid concentration

Fig. 5 shows the percentage leaching of copper and gold as a function of acid concentration in the range 0.01–2.0 mol/L at a fixed chloride concentration of 2.0 mol/L by adding NaCl and 25 °C when electro-generated chlorine at 714 A/m^2 current density (2.0 A current) was passed in the leach reactor. Raising the acid concentration to 1.0 mol/L at a fixed chloride concentration (2.0 mol/L) has increased the copper leaching with a substantial decrease of gold leaching till the period of 60 min. One of the most important factors in the chloride leach system is the pH level, since chlorine chemistry is pH dependant [8,16,17]. Fig. 6 shows the chlorine distribution with pH in acidic range which is calculated from the equilibrium constants given in Eqs. (2) through (4). When the pH falls below 2, dominant species of chlorine are $Cl_{2(aq)}$, Cl_3^-, and above pH 2 HClO is the dominant species. Besides, hypochlorous acid (HClO) (Eq. (6)) has a higher oxidizing power towards gold which is evident from the lower ΔG value than that with aqueous chlorine to form $AuCl_4^-$ complex (Eq. (5)). As acid concentration increases, the distribution

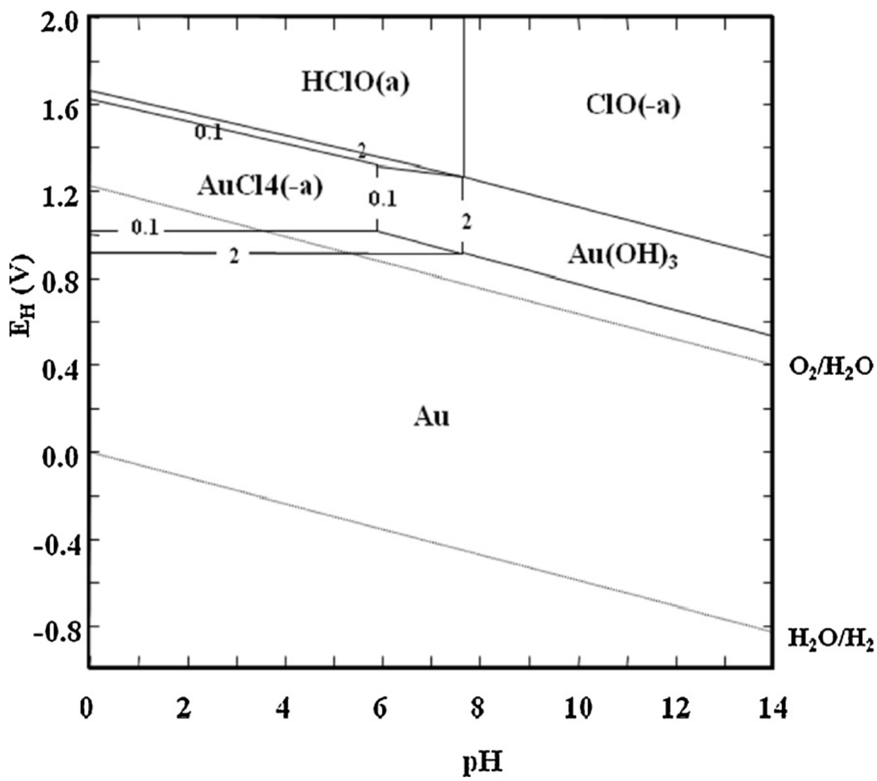

Fig. 4. Au–Cl–H_2O system at 25 °C ({Cl^-} = 0.1, 2 mol/L, {Au} = 0.5 × 10^{-3} mol/L).

of the hypochlorous acid decreases and disappeared at the concentration of acid >1.0 mol/L. Since the gold leaching increased with decreasing acid concentration (Fig. 5(b)) thus gold leaching seems to mainly depend on the concentration of hypochlorous acid and consequently on the oxidation potential as well. On the other hand, copper leaching increased with increasing acid concentration as shown in Fig. 5(a). Therefore, copper leaching may be dependent on the solubility of chlorine regardless of oxidation power of chlorine species.

3.1.2. Effect of temperature

Fig. 7 shows the pattern of the percentage leaching of copper (Fig. 7(a)) and gold (Fig. 7(b)) from the PCBs sample in solution as a function of temperature at a fixed HCl concentration of 2.0 mol/L and applied current density of 714 A/m^2 (2.0 A current) to generate chlorine gas. As can be seen a decrease in temperature increased the percentage leaching of copper while gold leaching mostly decreased. It is evident from Fig. 7(a) that the leaching of copper followed the order for temperature 25 °C > 35 °C > 50 °C in 120 min, with the copper leaching of 75.4%, 58.5%, and 53.5%, respectively. The leaching of gold (Fig. 7(b)) was retarded in initial stages at all temperatures when the copper leaching was active. In particular the low gold leaching rate was noticed up to 40 min at 25 °C correspond to the lowest concentration of residual chlorine and thereafter it increased drastically with increasing concentration of residual chlorine which meant high oxidizing condition. It was reported that the leaching of copper and gold was controlled by diffusion [18] and chemical reaction [19], respectively. Accordingly, the gold leaching would be more affected by temperature than that of copper. However, in this system the chlorine solubility [20] and residual chlorine concentration (Fig. 7(b)) seem to play the major role.

3.1.3. Effect of initial concentration of chlorine

The percentage leaching of copper and gold as a function of initial concentration of chlorine in 2.0 mol/L HCl solution at 25 °C and 714 A/m^2 current density (2.0 A current) is given in Fig. 8. The initial chlorine supplied from the anode in the electrolytic cell was titrated by the iodide–thiosulfate method to analyze total aqueous chlorine concentration [13]. As presented in Fig. 8(a), raising the initial concentration of chlorine increased the extent of copper leaching till 60%. Subsequently, the increase of copper leaching was almost similar regardless of the initial concentration of chlorine. Interestingly the gold leaching (Fig. 8(b)) was rapid with increasing initial concentration of chlorine due to presence of sufficient oxidants. Also, when the initial concentration of chlorine was increased from 0 to 3.46 g/L, the leaching of gold started rapidly and the retardation of gold leaching disappeared. This indicated that copper and gold can be selectively leached by adjusting the concentration of chlorine in the solution.

3.1.4. Effect of particle size

The percentage leaching of copper and gold as a function of particle size at 25 °C, 2.0 mol/L HCl, 17 g/L pulp density and 714 A/m^2 (2.0 A current) current density is given in Fig. 9. As is evident from Fig. 9(a), decreasing the particle size increased the extent of copper leaching from 30% to 97% in 120 min. Gold leaching (Fig. 9(b)) was retarded with decreasing particle size although, the effect was not that severe when sample without cutting (average size – 35 mm × 40 mm) was treated. Mention may particularly be made of the retarded dissolution of gold from the finest size particles (−2/+1 mm) with increased surface area due to the favorable copper leaching with the presence of insufficient chlorine thereafter to leach out gold. This may also be attributed to the galvanic effect for dissolving copper preferentially as compared to gold.

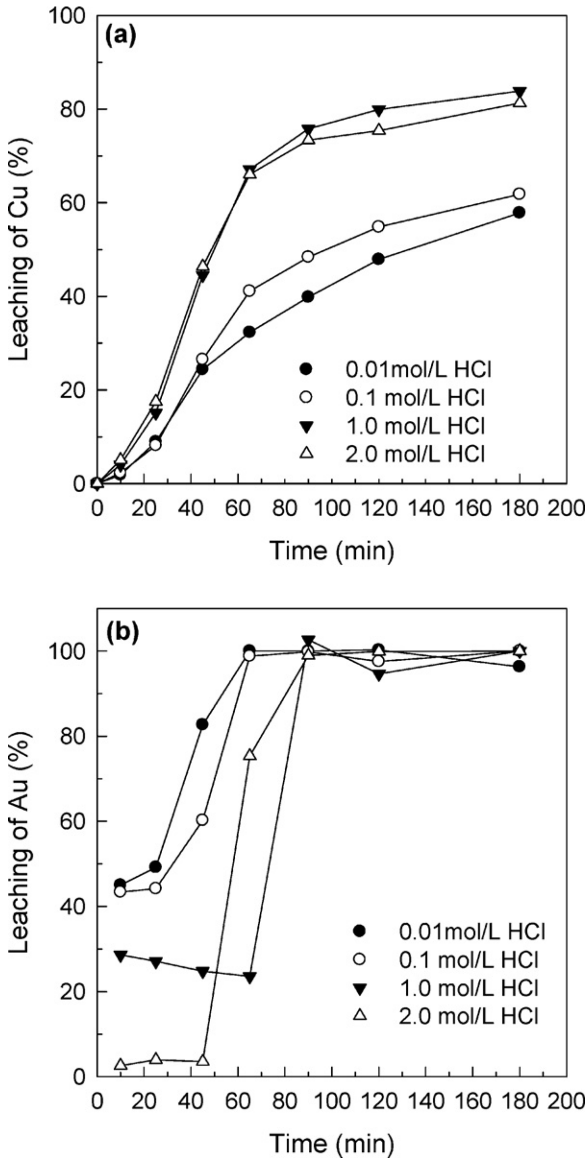

Fig. 5. Effect of acid concentration on (a) Cu and (b) Au leaching in fixed chloride concentration, 2.0 mol/L [Cl⁻] (current density, 714 A/m²; leaching time, 180 min; stirring speed, 600 rpm; pulp density, 17 g/L; temperature, 25 °C; particle size, −3/+2 mm).

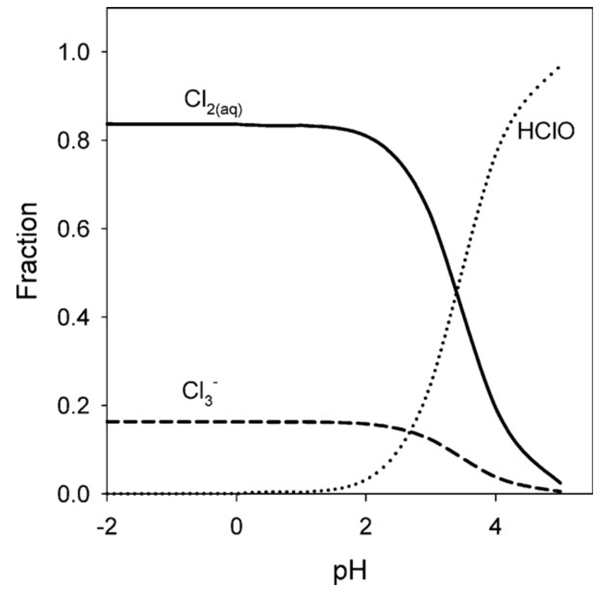

Fig. 6. Chlorine distribution with pH at 25 °C.

3.1.5. Effect of pulp density

The leaching behavior of copper and gold was investigated while varying the pulp density in 2.0 mol/L HCl solution at 25 °C and 180 min leaching time by electro-generated chlorine at 714 A/m² (2.0 A current) current density. Fig. 10 shows the copper leaching with time and copper concentration in 180 min with increase in the pulp density. As can be seen the increase in pulp density from 17 to 40 g/L resulted in the copper leaching of around 97% or slightly lower in 180 min. At a pulp density above 40 g/L the leaching rate decreased due to the insufficient concentration of chlorine. Therefore, the pulp density of 40 g/L may be considered as optimum for copper leaching at 25 °C in 180 min under the above conditions with the maximum leaching of 95% and the concentration of 25 g/L Cu in the solution.

The leaching of gold from the PCBs sample was investigated at 25 °C with time under the same condition as given in Fig. 10 and results are plotted in Fig. 11. It is apparent that the starting point of gold leaching was retarded with increasing pulp density from 17 to 45 g/L. In all cases the leaching of gold was very low (Fig. 11) till major part of copper dissolved (Fig. 10) and then increased to almost completely within a short time. The leaching of gold was particularly below 5% in 165 min and after that it drastically increased to 99% even at the high pulp density of 40 g/L. From this result it appears that gold and copper can be selectively leached by electro-generated chlorine in 2.0 mol/L hydrochloric acid solution for 165 min at 40 g/L pulp density and 25 °C.

To recover copper and gold selectively, the leaching process by electro-generated chlorine was divided into two stages (Table 2), leach-1 and leach-2. The 1st stage leaching with electro-generated chlorine with the particles of size −2/+1 mm was terminated at the optimum condition such as: pulp density – 40 g/L, leaching time – 165 min, temperature – 25 °C, and acid concentration – 2.0 mol/L HCl, for which the ORP value was below 350 $mV_{Ag/AgCl}$. In the leach liquor the concentrations of copper and gold were found as 24.0 g/L and 0.9 mg/L, respectively. After filtration, the residue was leached again in 0.1 mol/L HCl solution by electro-generated chlorine with 714 A/m² (2.0 A current) current density (2nd stage leaching) at 25 °C, leaching time 10 min and pulp density 160 g/L. Gold was leached out almost completely (93%, ∼67 mg/L) with more diluted concentration of copper (607 mg/L) in solution than that obtained in satge-1. It may be noted that the copper concentration in the 2nd stage leaching was 40 times lower than that of the 1st stage and gold was concentrated 4 times higher.

3.2. Gold recovery from the leach liquor

3.2.1. Adsorption by Amberlite XAD-7HP

In order to recover gold after leaching, preconcentration and separation procedure is necessary. Gold can be recovered from leach liquors using ion exchange resins. For selective Au(III) adsorption, three different resins such as a nonionic (Amberlite XAD-7HP) and strong base resins (Bonlite BA304 and Purolite A-500) were used [21]. The results from the gold sorption experiments are summarized in Table 3. As can be seen, these resins are non-selective for gold and the adsorption values are almost similar. Copper ions are more selectively adsorbed on the resins rather than gold ions due to their high concentration. The gold and copper ions loaded onto the resins can be selectively desorbed using different eluents for the two metals [22]. As reported earlier the Au(III) ions on the non-ionic resin such as Amberlite XAD-7HP, can be eluted easily rather than that of the strong base resins without loss of

Table 2
Leaching results by electro-generated chlorine from waste mobile phone PCBs.

Leaching stage	Optimum condition	Leaching		Concentration	
		Cu (%)	Au (%)	Cu (g/L)	Au (mg/L)
1st stage (ORP < 350 $mV_{Ag/AgCl}$)	40 g/L; 714 A/m^2; 2.0 mol/L HCl; 165 min; 25 °C	94.91	5.0	24.0	0.9
2nd stage (ORP > 1100 $mV_{Ag/AgCl}$)	160 g/L; 714 A/m^2; 0.1 mol/L HCl; 10 min; 25 °C	0.58	93.06	0.61	67

subsequent loading capacity [21,22]. Therefore, Amberlite XAD-7HP was chosen for the separation of copper and gold. In order to get more concentrated gold solution with lower concentration of copper as described above, the process of the 2nd stage leaching by electro-generated chlorine was adapted repeatedly to generate sufficient leach liquor which after filtration was subjected to the ion exchange process. To determine the metal loading capacity of Amberlite XAD-7HP, the leach liquor was passed to the column containing 1 BV (4.6 mL) of the resin and the metal recoveries were investigated. The adsorption capacity is the maximum metal quantity taken up by 1 g (1 BV) of the resin and expressed as mg Au/1 BV resin. The breakthrough curve (plot of C_e/C_o vs. BV) presented in Fig. 12 shows the loading behavior of gold that may be recovered from the solution in a fixed bed. After a solution BV of 115, an increase of gold concentration in the raffinate was observed (Fig. 12, where C_e: the final concentration of metal in the solution (mg/L) and C_o: the initial concentration (mg/L) in the solution). Gold

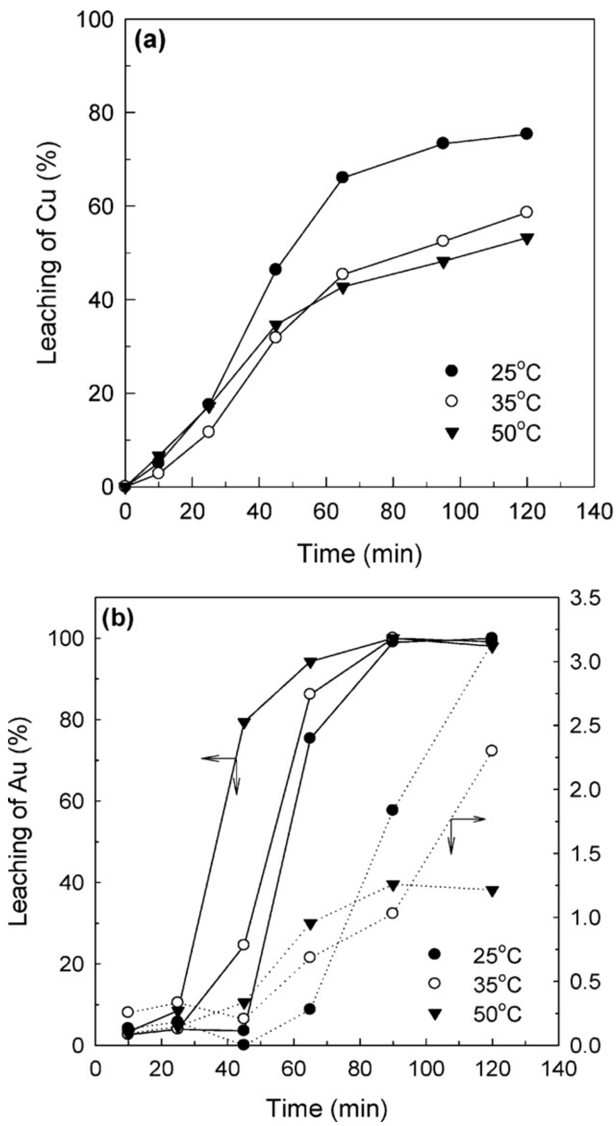

Fig. 7. Effect of temperature on (a) Cu and (b) Au leaching and residual $Cl_{2(aq)}$ in 2 mol/L HCl (current density, 714 A/m^2; leaching time, 120 min; stirring speed, 600 rpm; pulp density, 17 g/L; particle size, −3/+2 mm).

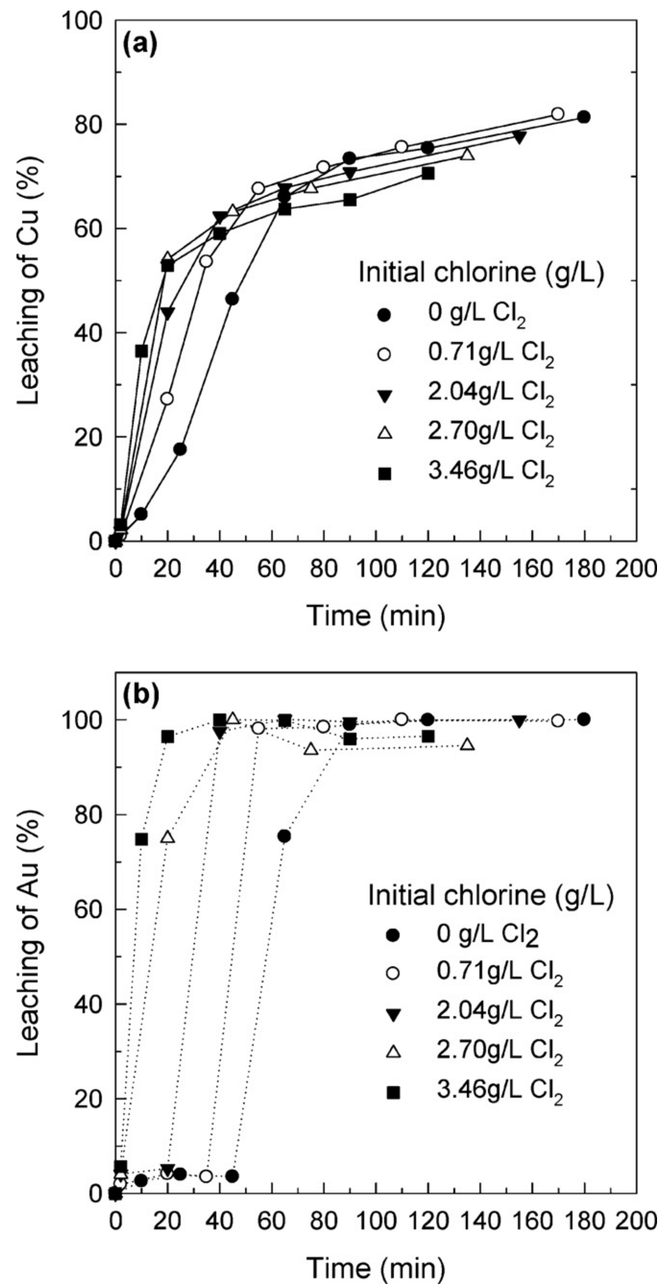

Fig. 8. Effect of initial concentration of chlorine on (a) Cu and (b) Au leaching in 2.0 mol/L HCl (current density, 714 A/m^2; leaching time, 180 min; stirring speed, 600 rpm; pulp density, 17 g/L; temperature, 25 °C; particle size, −3/+2 mm).

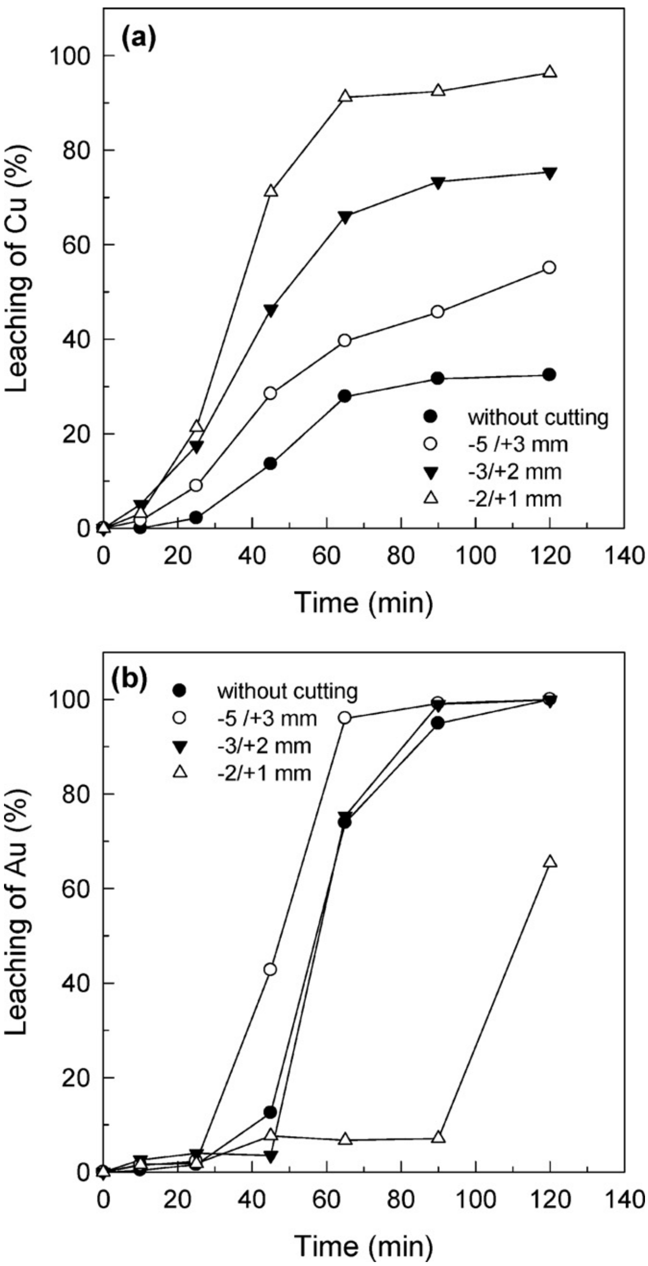

Fig. 9. Effect of particle size on (a) Cu leaching and (b) Au leaching in 2.0 mol/L HCl (current density, 714 A/m^2; stirring speed, 600 rpm; temperature, 25 °C; pulp density, 17 g/L; leaching time, 120 min).

recovery from the leach liquor by ion exchange using Amberlite XAD-7HP resin was thus 95%. The maximum amount of gold loaded on 1 g resin was calculated to be 46.03 mg. Under this condition the copper also adsorbed on the resin along with gold, which was around 5% (30 mg/L) of the initial copper concentration of the leach liquor.

Table 3
Adsorption results by various resins from 2nd stage leach liquor (leach liquor composition: 610 mg/L Cu, 67 mg/L Au, 0.5 pH).

Name of resin	Types	Adsorption			
		Cu (mg/L)	Au (mg/L)	Cu (%)	Au (%)
Amberlite XAD-7HP	Non-ionic	596	5.3	97.70	7.9
Bonlite BA304	Strong base	596	4.9	97.70	7.3
Purolite A-500	Strong base	580	4.7	95.08	7.0

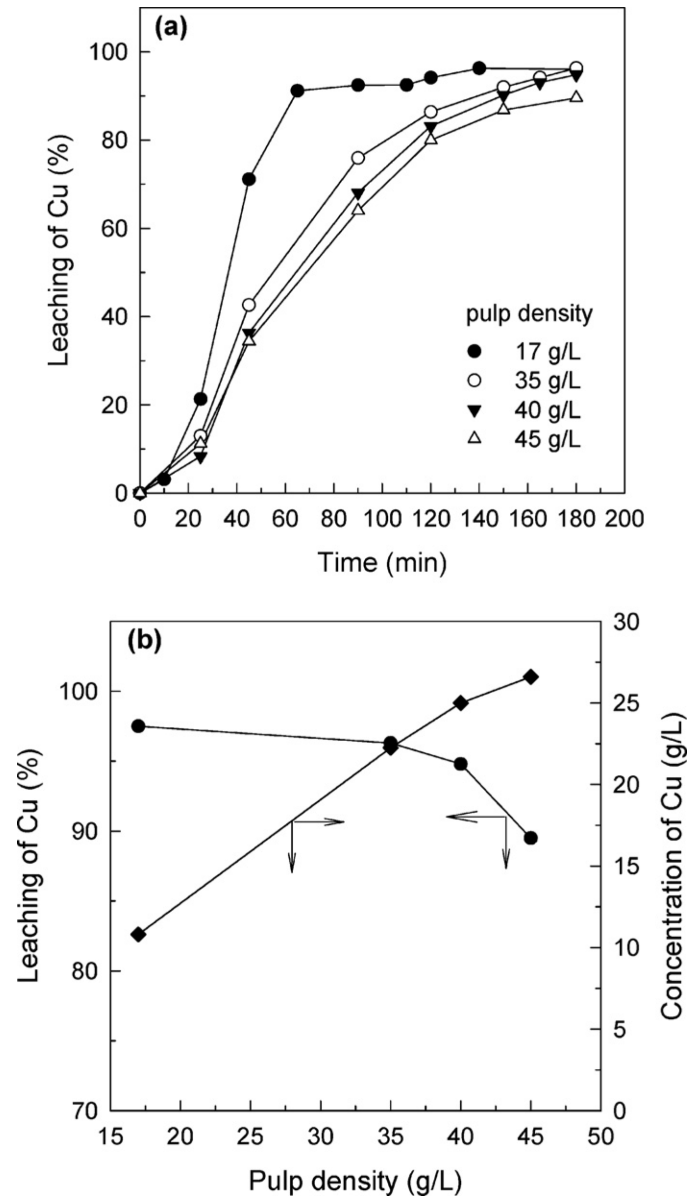

Fig. 10. (a) Leaching of Cu vs. time and (b) leaching and concentration of copper vs. pulp density at 180 min (current density, 714 A/m^2; stirring speed, 600 rpm; temperature, 25 °C; leaching time, 180 min; particle size, −2/+1 mm).

3.2.2. Elution and enrichment of the gold from the resin

The elution experiments were carried out to separate gold and copper from the loaded resins. The hydrochloric acid is effective reagent for the elution of copper but not suitable for gold [22]. Harris et al. [23] suggested the use of a mixture of acetone and diluted hydrochloric acid for achieving gold elution. Therefore, the loaded resin was eluted initially with a hydrochloric acid solution and then with a mixture of acetone and hydrochloric acid for recovery of copper and gold, respectively. Preliminary experimental results show that the elution of copper from the loaded resin was not affected by the concentration of hydrochloric acid. Therefore, the concentration of hydrochloric acid was selected as 0.1 mol/L HCl for eluting copper (770 mg/L). During the elution of copper prior to gold elution no Au(III) was eluted. And then the loaded resin was eluted again with a mixture of acetone and hydrochloric acid (1.0 mol/L) at a ratio of 9:1 for the gold recovery. The elution curve of gold from Amberlite XAD-7HP is presented in Fig. 13. The eluent flow rate through the column was maintained at 1 mL/min

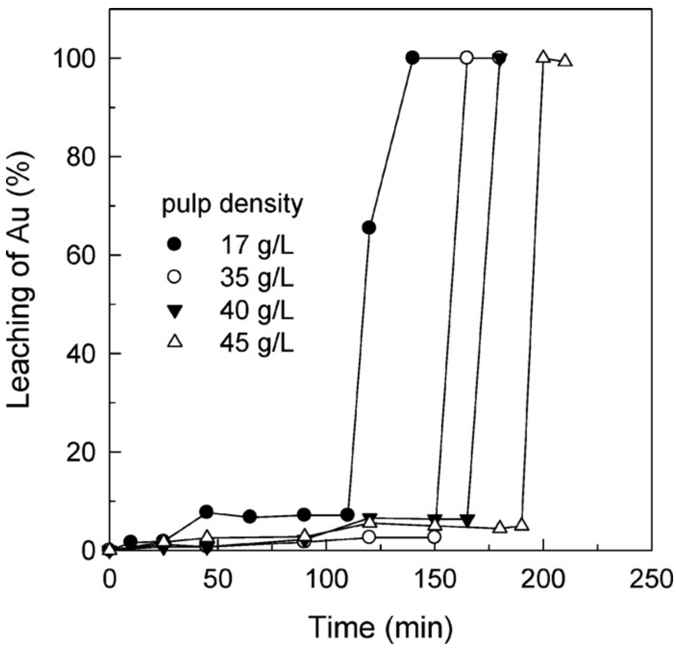

Fig. 11. Effect of pulp density on Au leaching in 2.0 mol/L HCl (current density, 714 A/m^2; stirring speed, 600 rpm; temperature, 25 °C; particle size, −2/+1 mm).

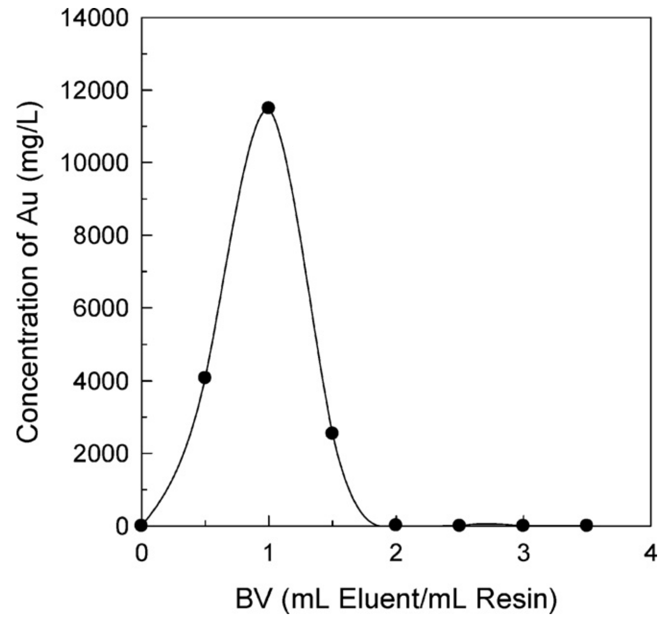

Fig. 13. Elution profiles of Au(III) loaded on Amberlite XAD-7HD by 1.0 mol/L HCl in acetone (eluent: a mixture of acetone and 1.0 mol/L HCl, ratio of acetone and hydrochloric acid = 1:9, flow rate = 1.0 mL/min).

and total elution occurred at 2 BV of eluent. A maximum 170–fold concentration (11,700 mg/L Au/BV, Fig. 13) of the initial gold solution was obtained in the ion exchange/elution process. After elution with 1.0 mol/L HCl in acetone, the concentration of 6034 mg Au/L could be enriched with 99.9% purity, which is 100 times higher in comparison to the concentration of this metal in the 2nd stage leach liquor.

3.3. Suggested process for the recovery of gold from mobile phone PCBs

Fig. 14 shows the suggested process flow-sheet for the recovery of gold and copper from mobile phone PCBs. During the 1st stage of electro-generated chlorine leaching, copper can be dominantly leached out to get a high concentration (around 24.0 g/L) with negligible amount of gold (<5%). The concentrated copper solution in the leach liquor (1st stage) can be subjected to the copper recovery process such as electrowinning at the cathode in the electrolytic cell after purification, whereas the gold in the residue from the leach-1 stage can be processed through the 2nd stage leaching by

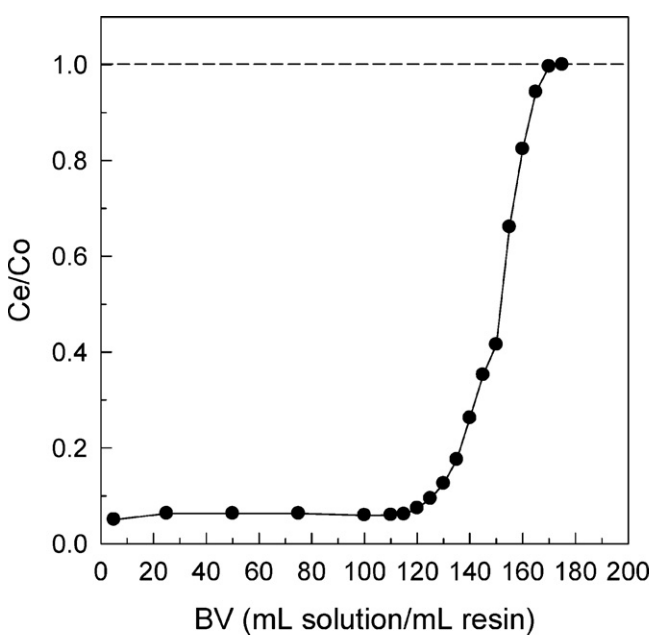

Fig. 12. Breakthrough profiles of gold (feed concentration: Au = 67 mg/L, Cu = 607 mg/L, Flow rate = 60 mL/min, wt. of Amberlite XAD-7HD packed in the column = 1.0 g).

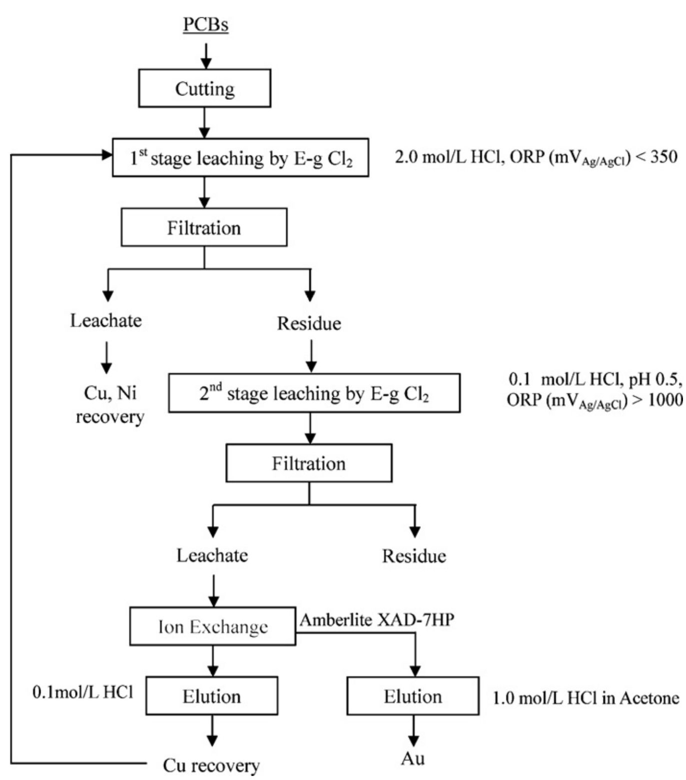

Fig. 14. The suggested process for the recovery of gold and copper from mobile phone PCBs.

electro-generated chlorine. The 2nd stage of leaching by electro-generated chlorine has the advantages as follows:

(1) Concentrating gold solution (more than 4 times than that of 1st stage) by increasing the pulp density of residue
(2) Lowering the metal concentration ratio of [Cu]/[Au] from 1000 to ~10 in the leach solution
(3) Recovery of copper in cuprous state which saves electrical energy to generate chlorine as well as to recover copper
(4) Operation in low acidity conditions

The solutions from the 2nd stage of leaching can then be treated for gold recovery by ion exchange resin using Amberlite XAD-7HP. The elution of metals from the loaded resin separately with hydrochloric acid and a mixture of hydrochloric acid and acetone, provides an effective method to separate and recover copper and gold, respectively. The copper solution (~770 mg/L) after elution by hydrochloric acid can be recovered as metal powder [24] by reduction with hydrogen gas, which is generated in the cathode compartment of the electrolytic cell (Fig. 2). The elution of the gold complex loaded in resin again with a mixture of hydrochloric acid and acetone, facilitates gold concentration to 6034 mg/L without contamination with copper. Pure gold metal can be obtained from the enriched solution by electrowinning process or reduction with $H_{2(g)}$ obtained from cathode compartment of the electrolytic cell.

4. Conclusions

In this work, leaching of gold from mobile phone PCBs by electro-generated chlorine and enriching the concentration of purified gold solution from the hydrochloric acid media by ion exchange procedure using Amberlite XAD-7HP, a non ionic resin were investigated. The following conclusions are drawn:

(1) The leaching efficiency of gold increased with increasing temperature and dissolved initial chlorine concentration, besides lowering the amount of acid in a fixed chloride concentration.
(2) In a two-stage leaching process the selective dissolution of copper and gold using electro-generated chlorine was achieved. In the 1st stage leaching the maximum copper recovery in 2 mol/L HCl solution was 97% in 165 min at 25 °C and 40 g/L pulp density, while the gold leaching was below 5%. High leaching of gold (93%, ~67 mg/L) was obtained along with residual copper (770 mg/L) in the 2nd stage of leaching with a diluted acid solution (0.1 mol/L HCl) at 25 °C and a higher pulp density of 160 g/L. The experimental results clearly demonstrate that copper and gold can be mostly separated during leaching stage itself by adjusting the solution acidity and chlorine concentration.
(3) Gold was recovered from the solution of the 2nd stage of chlorine leaching by ion exchange using Amberlite XAD-7HP. The concentration of gold was enriched during elution with 1.0 mol/L HCl in acetone (1:9) to 6034 mg/L (99.9% purity) without any contamination with copper. Prior to gold elution the small amount of copper loaded to the resin was selectively recovered by contacting with 0.1 mol/L hydrochloric acid.

A process flow-sheet is suggested to recover gold and copper from the mobile phone PCBs.

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References

[1] F. Ongondo, I. Williams, Mobile telephone collection, reuse, and recycling in the UK, in: Third BOKU Waste Conference, 2009.
[2] J. Cui, L. Zhang, Metallurgical recovery of metals from electronic waste: a review, J. Hazard. Mater. 158 (2008) 228–256.
[3] P. Quinet, J. Proost, A.V.X. Lierde, Recovery of precious metals from electronic scrap by hydrometallurgical processing routes, Miner. Metal. Process. 22 (2005) 17–22.
[4] S. Kulandaisamy, J.P. Rethinaraj, P. Adaikkalam, G.N. Srinvasan, M. Raghavan, The aqueous recovery of gold from electronic scrap, JOM 8 (2003) 35–41.
[5] V.H. Hung, J.-c. Lee, J. Jeong, H.T. Hai, M.K. Jha, Thiosulfate leaching of gold from waste mobile phones, J. Hazard. Mater. 17B (2010) 1115–1119.
[6] C. Abbruzzese, P. Fornari, R. Massidda, F. Vegliό, S. Ubaldini, Thiosulphate leaching for gold hydrometallurgy, Hydrometallurgy 39 (1995) 265–276.
[7] P.P. Sheng, T.H. Etsell, Recovery of gold from computer circuit board scrap using aqua regia, Waste Manage. Res. 25 (2007) 380–383.
[8] M.I. Jeffery, P.L. Breuer, W.L. Choo, A kinetic study that compares the leaching of gold in the cyanide, thiosulfate, and chloride systems, Metal. Mater. Trans. 32B (2001) 979–986.
[9] A.G. Chmielewski, T.S. Urbańnski, W. Migdal, Separation technologies for metals recovery from industrial wastes, Hydrometallurgy 45 (1999) 333–344.
[10] E-y. Kim, M.-s. Kim, J.-c. Lee, M.K. Jha, K. Yoo, J. Jeong, Effect of cuprous ions on Cu leaching in the recycling of waste PCBs, using electro-generated chlorine in hydrochloric acid solution, Miner. Eng. 21 (2008) 121–128.
[11] E-y. Kim, M.-s. Kim, J.-c. Lee, M.K. Jha, K. Yoo, J. Jeong, Leaching behavior of copper using electro-generated chlorine in hydrochloric acid solution, Hydrometallurgy 100 (2010) 95–102.
[12] E-y. Kim, M.-s. Kim, J.-c. Lee, K. Yoo, M. Kumar, Leaching of metal components from waste printed circuit boards using electrogenerated chlorine in hydrochloric acid solution, in: Proceedings of the Conference on Jim Evans Honorary Symposium. TMS 2010 Annual Meeting & Exhibition, Seattle, Washington, USA, February 17, 2010, pp. 233–239.
[13] I.M. Kolthoff, E.B. Sandell, E.J. Meehan, S. Bruckenstein, Quantitative Chemical Analysis, The MacMillan Company, New York, 1971.
[14] R. Radulescu, A. Filcenco-Olteanu, E. Panturu, L. Grigoraş, New hydrometallurgical process for gold recovery, Chem. Bull. “POLITEHNICA” 53 (2008) 135–139.
[15] HSC Chemistry 5.1, Chemical Reaction and Equilibrium Software, Outotec, 2002.
[16] R. Winand, Chloride hydrometallurgy, Hydrometallurgy 27 (1991) 285–316.
[17] H. Majima, Y. Awakura, K. Tsugui, E. Peters, Fundamental studies on chlorine behavior as related to zinc electrowinning from aqueous chloride electrolytes, Metal. Trans. 21B (1990) 251–258.
[18] O. Herreros, R. Quiroz, J. Viñals, Dissolution kinetics of copper, white metal and natural chalcocite in Cl_2/Cl^- media, Hydrometallurgy 51 (1999) 345–357.
[19] J. Viñals, C. Núñez, O. Herreros, Kinetics of the aqueous chlorination of gold in suspended particles, Hydrometallurgy 38 (1995) 125–147.
[20] M. Alkan, M. Oktay, M. Çopur, Solubility of chlorine in aqueous hydrochloric acid solutions, J. Hazard. Mater. 119 (2005) 13–18.
[21] N.V. Nguyen, J. JeongJ, M.K. Jha, J.-c. Lee, K. Osseo-Asare, Comparative studies on the adsorption of Au(III) from waste rinse water of semiconductor industry using various resins, Hydrometallurgy 105 (2010) 161–167.
[22] N.V. Nguyen, J.-c. Lee, S.-k. Kim, M.K. Jha, K.-S. Chung, J. Jeong, Adsorption of gold(III) from waste rinse water of semiconductor manufacturing industries using Amberlite XAD-7HP resin, Gold Bull. 43 (2010) 200–208.
[23] B.G. Harris, J.P. Barry, S. Monette, Recovery of gold from acidic solutions, US Patent 5,028,260 (1990).
[24] A. Agrawal, V. Kumar, B.D. Pandey, K.K. Sahu, A comprehensive review on the hydrometallurgical process for the production of nickel and copper powders by hydrogen reduction, Mater. Res. Bull. 41 (2006) 879–892.