Chapter 2
Electronic Waste: Generation and Management

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2.1 Electronic Waste in the World

The electronics industry is one of the most important industries in the world. It has grown steadily in recent decades, generates a great number of jobs, promotes technological development and, at the same time, fuels a high demand for raw materials that are considered scarce or rare (e.g. precious metals and rare earths elements).

This development affects the environment in two ways: first through the large and growing amount of equipment that is discarded annually and second through the extraction of natural raw materials to supply the demand of the new equipment industry. Both can be measured by the amount of equipment that is produced and discarded annually by many countries.

The main manufacturers and generators of electronic waste are considered to be developed or developing countries. According to Robinson [1], most electronic waste is generated in Europe and the United States. However, China, the countries of Eastern Europe and Latin America are becoming large generators of electronic waste.

Estimates indicate that about 40 million tonnes of this waste are generated each year, or approximately 5 % of all solid waste generated in the world [2]. Another study, from Greenpeace, estimated that globally 20–50 million tonnes of WEEE (waste electrical and electronic equipment) are discarded annually, with Asian countries disposing up to 12 million tonnes [3].

Robinson [1] also estimated that computers, mobile phones and television sets alone would correspond to 5.5 million tonnes of electronic waste generated on a

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global scale in 2010. Moreover, for 2015, this figure was projected to be 9.8 million tonnes. According to the author, by volume electronic waste may correspond to about 8 % of all municipal waste generated.

For monitors there is no specific number on the amounts discarded annually. However, for some countries, like the USA, China and Taiwan, it is estimated that 3.2 million, 5 million and 1 million televisions and monitors, respectively, are disposed of annually [1].

Similarly, in relation to computers, there is no exact number for discarded equipments, but this number may be assumed to be proportional to the quantity of computers in use worldwide. According to the Computer Industry Almanac [4], the number of computers in use worldwide in the 80s was 4.8 million. In 2000 this number had increased to 553 million and for 2015 a number of 2,020–2,070 million has been projected. The 5 countries with the largest number of computers in use until the end of 2011 were USA (310.6 million), China (195.1), Japan (98.1), Germany (71.5) and India (57).

World data indicate that, in 2011, 372 million PCs were sold worldwide and sales are projected to hit 517 million units by 2015. The three countries with the highest sales in 2011 were China, USA and Brazil [4].

The life cycle of many electronic goods has been substantially shortened due to advancements in electronics, attractive consumer designs, marketing and compatibility issues. For example, the average life cycle of a new computer has decreased from 4.5 years in 1992 to an estimated 2 years in 2005 and is further decreasing [5].

According to the Basel Action Network (BAN), an organization that tracks the flow of toxic waste in the world, eight in ten unused computers in the USA end up in Asian countries, such as India and China, where recycling costs are lower. Africa has also become a center for the receipt of electronic waste [6].

Data from the United Nations (UN) for 2005 quantified the per capita generation of electronic waste in developing countries. According to this study, Brazil and Mexico are the developing countries that generate the most electronic waste from computers, with about 0.5 and 0.45 kg/person/year, respectively, ahead of such countries as South Africa, with 0.4 kg/person/year, and China, with 0.2 kg/person/year [7].

In addition to computers, mobile phones are another type of electrical and electronic equipment with great production and sales.

In the USA, an EPA survey showed that approximately 125 million mobile phones are discarded annually, which means 65,000 tonnes of electronic waste. The same survey showed that a mobile phone has an average life cycle of 9–18 months [8].

Another study has shown that the global number of obsolete mobile phones is estimated to be more than 500 million and continues to grow rapidly [9]. In November 2013, the number of mobile phones in use in Brazil reached 271 million, i.e., well above the Brazilian population, which is 200 million [10].

As far as the recycling of mobile phone devices is concerned, there are no concrete data on recycling rates in the world, but research conducted by Nokia in 13 countries showed that only 3 % of mobile phones are recycled [11].

Currently, the lion's share of electronic waste comes from computers, mobile phones, televisions, monitors, cathode ray tubes (CRT) and printers [12]. However, new technologies such as liquid crystal display (LCD) are now replacing older devices, generating new types of electronic waste.

In developing countries like China and India, low cost and easy operation result in most electronic waste being further treated in backyards or small workshops using primary methods such as open burning and acid wash, especially in order to recover metals of economic interest [13].

At the same time, large companies like Umicore, Noranda, Boliden, and Cimélia, among others, have published papers on the process of refining metals, mainly in order to recover precious metals. These industries process various types of industrial wastes and by-products of non-ferrous metals, including Printed Circuit Boards (PCBs), recovering about 20 precious metals and other non-ferrous metals. The processes used follow a complex flowchart, with several steps that include pyrometallurgical, hydrometallurgical and electrochemical techniques and operations [14–17]. Considering that information and communication technologies continue to spread throughout the world, recycling technologies must be well managed and established worldwide.

2.2 The Problem of WEEE

Several environmental protection agencies around the world consider WEEE to be hazardous waste because they have chemicals compounds in their composition that are toxic and harmful to human health and to the environment [18, 19].

The chemical composition of WEEE varies according to each product. For example, LED TVs have a higher amount of polymer, while stoves and microwaves have a larger amount of metals. In fact, the chemical composition depends on several factors, such as the type of WEEE, year of manufacture, manufacturer's brand and country of origin. Usually, WEEE are classified by type, using the regulations of environmental agencies, such as Directive 2002/96/EC of the European Union [20].

In general, a mixture of metals can be found in WEEE, such as copper, iron, aluminum, brass and even precious metals, such as gold, silver and palladium, in addition to a mixture of polymers, such as polyethylene, polypropylene, polyurethane and others. WEEE may also include ceramic materials, such as glass, and other inorganic, organic and even radioactive materials [1].

WEEE is considered toxic to human health and to the environment because it often has inorganic compounds in its composition, such as mercury, lead, cadmium, nickel, antimony, arsenic and chromium, in addition to such organic compounds as polychlorinated biphenyls, chlorofluorocarbons, polycyclic aromatic hydrocarbons and polyhalogenated, among others [1].

The concentration of these compounds and substances in WEEE varies with the product type, year of manufacture and the manufacturer itself. For example, old refrigerators contained chlorofluorocarbon refrigerant, but with the development of the Montreal Protocol in 1989, and its ratification by member countries, the manufacturers of refrigerators replaced this toxic gas by another inert gas in the new refrigerator models [21].

Some efforts have been made to prevent/reduce the use of toxic products in electronics equipment. The most important was, probably, Directive 2002/95/EC of the European Union, also known as RoHS—Restriction of Certain Hazardous Substances [22]. This resolution banned the manufacture and sale of consumer electronics in the European Union that containing lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and/or polybrominated diphenyl ethers. As such, many countries that have trade relations with the EU were obliged to manufacture products without these substances.

Despite these efforts, WEEE disposal is still a worldwide challenge, since in many countries there is no structured system of reverse logistics and most WEEE is still disposed in landfills or in the open places exposed to the weather [23–26]. This form of disposal can contaminate the soil or subsoil with metals and/or toxic substances from WEEE. Some studies, such as those by the EPA [27] and Spalvins [28], show that contamination by WEEE in landfills is difficult to quantify because there are many external factors affecting the decomposition of chemicals, including temperature, pressure, pH, and oxygenation of the medium, among others. In another EPA study [29], it is pointed out that 2–5 % from all solid waste sent to landfills in the USA comes from electronic waste.

The incineration of WEEE is an alternative to landfill, but can also cause environmental problems. Many components of WEEE have organic compounds in the composition that, when incinerated, can generate dioxins and furans [30]. The presence of halogens in WEEE can be explained by the addition of flame-retardants containing bromine. Approximately 12.5 % of all types of WEEE contain halogenated compounds [31]. If the burning of WEEE is performed without proper environmental precautions, the release of polybrominated polyphenyl compounds, and others like it, will occur. The primary means of preventing the release of dioxins and furans during the incineration of equipment is a gas treatment system. However, these are very expensive pieces of equipment for the companies that perform these services. As a result, many companies are burning without an adequate treatment of gases.

EPA studies [32, 33] regarding the disposal of WEEE in the USA showed that, in 2001, about 2 million tonnes of WEEE were generated, of which approximately 90 % was sent to landfills. In 2009, 2.37 million tonnes were generated, but the percentage of recycling reached 25 %, i.e., much higher than in 2001.

The recycling of WEEE is a growing trend around the world, but for a successful recycling process, the strategies and technologies used for the collection and processing of e-waste are very important. And although many countries already legislation in place dealing with e-waste, especially the countries of the European Union, Japan and the USA, the management of this waste is still deficient in the majority of countries around the world [34].

2.3 WEEE Management

Extensive research is currently under way into e-waste management in order to mitigate problems at both the national and international levels. Several tools have been developed and applied to e-waste management, including: LCA (Life Cycle Assessment), MFA (Material Flow Analysis), MCA (Multi Criteria Analysis) and EPR (Extended Producer Responsibility) [35].

These management tools, combined with the existing laws in different countries, can help improve the disposal of electronic waste in the world, increasing the reuse of materials and reducing environmental impacts.

In Europe, a number of legislative documents have been drafted and/or implemented requiring manufacturers and other stakeholders to adopt an environmental approach to design and assess the environmental impact of their products throughout their lifecycle [36]. The main laws and regulations are: the WEEE (Waste Electrical and Electronic Equipment) and the RoHS (Restriction of the Use of Certain Hazardous Substances) Directives, created by the European Union. The WEEE Directive makes manufacturers responsible for collecting, recycling and/or disposing of waste from electrical and electronic equipment. The RoHS Directive, which came into force in July 2006, prohibits the use of six hazardous substances in the manufacture of products, including electronics equipment. These substances are cadmium (Cd), mercury (Hg), lead (Pb), hexavalent chromium (Cr VI), polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) [37].

In Asia, the rapid economic growth in most countries is increasing the amounts of WEEE generated. In addition, Asian countries are the recipient of most of the WEEE generated globally. Ketai et al. [38] estimate that about 4K tonnes of WEEE are discarded globally per hour, 80 % of which is exported to Asia, with China receiving 90 % of this share. In March 2007, China has adopted legislation to control the pollution caused by electronic products, focusing on the restrictions of using hazardous substances in electronic equipment (unofficially referred to as China RoHS) [26]. In Japan, in order to decrease the environmental impact of WEEE, the Home Appliance Recycling Law (HARL) was introduced and adopted in April 2001 [39]. The law was enacted for four main sources of consumer WEEE in Japan, namely: refrigerators, washing machines, TVs and air conditioning units. In 2008, the law was revised to incorporate LCD and plasma TVsn and clothes dryers.

The basic principles of Japan's HARL are the replacement of toxic substances and the increase of recyclability, encouraging recycling and prohibiting inappropriate deposits. Through this law, the consumer pays a fee to recycle the product, with the government being responsible for the collection and for the reverse logistics system. The manufacturers are responsible for the recycling of materials and the proper reuse of toxic components, i.e., the responsibilities for the waste are shared. However, the HARL has been criticized for excluding certain types of WEEE, such as mobile phones. There is no recycling law that specifically targets mobile phone waste, despite the fact that more than 25 million units are discarded every year. It is estimated that only 40 % of mobile phone waste is collected by retailers [40].

As far as Africa is concerned, it is known that many African countries receive second-hand equipment. Most electronic equipment exports to Africa are not pre-tested for functionality. Consequently, it is not possible to assess whether these exports are legally defined as hazardous waste under the Basel Convention [41]. The Basel Convention was adopted on March 22, 1989 and came into force on May 5, 1992. It deals with the control of transboundary movements of hazardous waste and its deposits. This Convention provides that hazardous waste must be disposed of in the country of origin. The Base Convention considers electronic waste as hazardous and its export could be allowed only under special conditions [41].

Except for South Africa, where an increase in material recovery activities has been reported, data on the recycling of WEEE in Africa is scarce [42]. Despite working under generally deplorable social and environmental conditions, the informal collectors, dismantlers and recyclers in Africa are playing an increasingly important role in the processing of WEEE [43, 44].

Sales of electronic equipment in Latin/South American countries have increased rapidly, approaching the level of industrialized countries, with increasing WEEE generation as a result [45]. However, WEEE recycling is mostly restricted to disassembly companies. Although a number of traditional metal recycling companies in countries such as Chile, Argentina, Peru, Colombia and Brazil had discovered the WEEE recycling markets, processed quantities are still on a modest level [45]. Several countries are engaged in policy formulation related to WEEE, with Brazil seemingly the frontrunner in this issue [46]. In Brazil, the National Policy on Solid Waste enacted in August 2010 requires manufacturers, importers, distributors and retailers of electronics products and its components to structure and implement reverse logistics systems to collect the product after its use by consumers [47].

In North America, the USA is the main generator of electronic waste with approximately 7.5 kg/person/year [26]. Several states in the United States have implemented WEEE programs, but specific legislation is rare. Initiatives to adopt legislation on the federal level have not been successful so far [48, 49]. There are currently at least 20 states and one municipality (New York City) that have legislation about WEEE. In Canada, the situation is similar to the USA, i.e., there is no national legislation concerning electronic waste, but several provinces already have their own legislation [50].

The disposal of all this waste generated globally is extremely worrying. The best way to manage this waste is through the recycling of the materials present in it. The chemical composition of WEEE is extremely heterogeneous, varying according to the type of equipment, year of manufacture, manufacturer, and country of origin, among other factors. In fact, polymers, ceramics and metals can be recovered from electronic waste. The different metals present draw the greatest attentions because of their economic value. These metals may be present in different types of components, in variables amounts, pure or as alloys.

Printed circuit boards (PCBs), present in all types of electronics equipments, are of major interest because they are considered secondary raw materials that are rich in copper and precious metals such as gold, silver and palladium. For example, a single mobile phone can contain high concentrations of gold (24 mg), silver (250 mg) and palladium (9 mg) [51]. When compared to the average contents of the primary sources (minerals), these values reveal a secondary source of high metal concentration. This stimulates the recovery of these metals, ensuring metallic resources for future use and avoiding all environmental impacts related to their primary extraction [51].

Table 2.1 shows the concentration of metals found by several authors in the PCBs from mobile phones. One can see that the values are not entirely similar, due to the reasons mentioned above.

Considering this metal content, the management of WEEE for its recycling is increasing in every country. E-waste management is different in developed and developing countries. Overall, there are two types of facilities in developed countries engaged in the recycling chain, according to the nature of the methods involved. The first group contains the facilities that are principally engaged in the dismantling and mechanical processing of e-waste for the recovery of raw materials. The second group uses metallurgical processes to recover metals. In contrast, the e-waste recycling sector in developing countries is largely unregulated, and e-waste is often processed to recover valuable materials in small workshops using rudimentary recycling methods. The informal e-waste recycling prevalent in developing countries is associated with severe environmental pollution and occupational exposure to the e-waste-derived chemicals [58]. Although the costs of recycling can be smaller in backyards common to the developing countries, the use of large-scale processes enables the recovery of much higher yields of valuable substances, such as precious metals, than backyard operations. For relevant parts such as printed circuit boards, this higher yield usually overcomes the cost disadvantages [13].

Table 2.1 Metal concentration (wt%) of printed circuit boards reported in different studies

wt%	Sum [52]	Guo et al. [53]	Yang et al. [54]	Park and Fray [55]	Yamane et al. [56]	Tuncuk et al. [57]
Gold	0.1	0.008	–	0.025	0.00	0.035
Silver	0.2	0.33	–	0.100	0.21	0.138
Copper	20	26.8	25.06	16.0	34.49	13
Nickel	2	0.47	0.0024	1	2.63	0.1
Tin	4	1.0	–	3.0	3.39	0.5

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