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Electronic Waste Recycling and Disposal: An Overview

Cristina A. Lucier and Brian J. Gareau

Abstract

Electronic waste, or e-waste, is said to be the fastest growing stream of hazardous waste in the world. E-waste is comprised of a variety of inputs including hazardous materials, potentially valuable and recyclable materials, and other inputs. E-waste follows a range of pathways after disposal, including formal and informal recycling, storage, and dumping, in both developed and less-developed country contexts. Globally, the handling and regulation of e-waste as both a hazardous waste stream and as a source of secondary raw materials has undergone significant changes in the past decade. A growing number of countries have adopted extended producer responsibility laws, which mandate electronics manufacturers to pay for proper recycling and disposal of electronics. The e-waste recycling industry is becoming more formalized as the potential to recover valuable materials has increased, but a range of recent studies have shown that e-waste recycling continues to carry a range of occupational health and environmental risks.

Keywords: e-waste, waste electrical and electronic equipment, extended producer responsibility, Basel Convention

1. Introduction

Electronic waste, sometimes referred to as e-waste or waste electrical and electronic equipment (WEEE), is a highly varied stream of hazardous waste. This waste stream is comprised of any electronic items that a consumer or business intends to dispose of, or is no longer useful for its original purpose. E-waste has generated a considerable amount of public and political interest due to a confluence of factors, including: the exponential rise in the generation of e-waste, the potential value of recycling the waste in order to recover precious metals and other elements, and the environmental and human health risks associated with improperly storing, disposing of, and recycling e-waste. Some of the major responses to the rising generation of e-waste (and growing demand for secondary raw materials that it contains) have included the development of producer “take-back” legislation, technological innovations in recycling processes, and the formation of partnerships to facilitate the transfer of e-waste between the informal and formal recycling sectors [1].

E-waste is an incredibly complex waste stream, as it encompasses a wide range of items and the exact composition of many electronic components are considered to be trade secrets, meaning they are the confidential information of the manufacturer. Generally speaking, “modern electronics can contain up to 60 different elements; many are valuable, some are hazardous and some are both. The most complex mix of substances is usually present in the printed wiring boards (PWBs)” [2].

To use a specific example, the material content of a mobile phone includes “over 40 elements in the periodic table including base metals like copper (Cu) and tin (Sn), special metals such as cobalt (Co), indium (In) and antimony (Sb), and precious metals including silver (Ag), gold (Au), and palladium (Pd)” [2].

Electronics that had been used in industrial or business applications, such as medical equipment, have been recycled in the formal recycling industry for more than 40 years. These large items have frequently been exported within industrialized countries in the OECD to specialized facilities where they are processed for the purpose of extracting secondary raw materials. Consumer electronic waste from smaller items such as cell phones and televisions have not historically been profitable to recycle in countries with higher labor costs, since the quantity of recoverable valuable materials is relatively low. Hence, these items have typically either been disposed of, stored in consumers' homes, or exported (often illegally) to less developed countries such as China, India, Ghana and Nigeria, where they are recycled by informal recyclers using low-tech methods such as manual dismantling, open burning and acid leaching in order to recover gold, copper and other valuable metals. These methods generate subsistence livelihoods for workers but also result in significant hazards to human health and the environment as a result of the toxic materials that are also embedded in consumer electronics. This chapter will explore these conventional recycling efforts and the ways in which they are evolving alongside global economic developments and the introduction of new recycling processes and technologies.

Generally speaking, the e-waste recycling process consists of five basic stages: collection, toxics removal, preprocessing, end processing and disposal [3]. There are wide degrees of variation in how these stages are managed worldwide. For much of the global waste stream, e-waste may be collected informally via “waste pickers” or more formally through voluntary or mandatory producer “take-back” programs. In terms of consumer electronics, regions where e-waste is picked up by informal collectors have historically achieved significantly higher recycling rates than those where waste is dropped off through formal channels [4]. After reaching the recycling site, dangerous components that require special treatment (e.g., batteries, Freon) are removed. The units are then separated into more homogenous groups based on material. This can be done manually, mechanically or a combination of both. Manual dismantling involves tools such as screwdrivers, hammers and labeled containers, while mechanical dismantling may involve conveyor belts, giant shredders and magnets [5].

Following the separation and dismantling phases, more homogenous groups of material (e.g., gold, copper, plastic, circuit boards) are then treated through a refining process: this can be accomplished chemically, with heat, or with metallurgical processes. This stage can be as high-tech as a giant smelter in Antwerp, Belgium or as low-tech as acid stripping in a backyard in Guiyu, China. Research has uncovered how sites will often compete for the waste by offering low-cost strategies, sometimes described as a “race to the bottom” process of increasingly lower standards and environmental protection [6]. Finally, all of the components that cannot be sold or used as secondary raw materials are disposed of through means such as incineration or landfill.

The level of efficiency achieved through e-waste recycling depends upon the process that is followed, especially in the separation and dismantling phases. In dismantling electronics, manualized options are often much more effective than mechanized processes in gaining access to the best quality secondary raw materials. Mechanized take-back programs such as those in the E.U. do not even come close to the efficacy of the labor-intensive e-waste collection rates found in many African countries [4, 7]. Manual dismantling is also preferable to machine shredding, which

damages and does not completely separate individual materials. For example, while 90% of the gold in discarded mobile phones can be recovered when manually dismantled, only 26% is recovered through mechanical shredding [8]. However, these more labor-intensive options are not cost effective unless labor costs are extremely low [3].

2. Secondary raw materials recovered in electronic waste recycling

E-waste contains components that have historically been valuable in significant quantities, when the dismantling costs have been low enough [9]. Some of the applications and quantities extracted for different “important” or valuable elements within electronic devices are represented in **Table 1**.

In addition to these metals, there is also another subset of elements—known as rare earth elements—which are crucial to the functioning of the newest electronics, particularly those with LED lighting and touch screen technologies. Rare earth elements are available in abundant quantities globally, but the process of their extraction can create widespread environmental problems, including radioactive contamination [10]. **Table 2** provides a list of the rare elements that are used in various electronics. It is worth noting that the actual quantity of these elements used is relatively small, but that their properties are closely linked to the performance level of these technologies [11]. Rare earths play a particularly decisive role in the high performance functioning of magnets. The information provided in **Table 2** has been adapted from information derived from the U.S. Department of Energy, a report commissioned for the U.S. Interior Department and the U.S. Geological Survey, as well as industry trade publications [12–14]. Those rare earths considered to be of the highest potential resale value (and the highest risk for supply shortages) are neodymium (Nd), europium (Eu), dysprosium (Dy), terbium (Tb) and yttrium (Y) [12, 14].

Recent technological developments, including improvements to the mechanization process as well as pilot projects that combine low-tech and mechanized

Element	Main applications	Total tons/year [2006]
Silver	Contacts, switches, solders	6000
Gold	Bonding wire, contacts, integrated circuits	300
Palladium	Multilayer capacitors, connectors	33
Platinum	Hard disk thermocouple, fuel cell	13
Ruthenium	Hard disk, plasma displays	27
Copper	Cable, wire connector	4,500,000
Tin	Solders	90,000
Antimony	Flame retardant; CRT glass	65,000
Cobalt	Rechargeable batteries	11,000
Bismuth	Solders, capacitor	900
Selenium	Electro-optic copier, solar cell	240
Indium	LCD glass, solder, semiconductor	380

Source: [2].

Table 1.
A sample of valuable elements in electronic wastes.

Technology	Rare earths used
Electric and hybrid cars (NiMH battery)	Neodymium, praseodymium, dysprosium, terbium
Computers (magnets in hard disk drive)	Neodymium, praseodymium, dysprosium, terbium
Flat panel screens (glass coating to produce colors and brightness)	Yttrium, europium, terbium, gadolinium, praseodymium, cerium
MRI machines (magnets)	Neodymium, praseodymium, dysprosium, terbium, yttrium, europium
Smart phones (magnets and speakers)	Neodymium, praseodymium, dysprosium, terbium, yttrium, europium
Other uses (including “chemicals, military weapons and delivery systems, and satellite systems” ([13], p. 12)	Cerium, lanthanum, yttrium, neodymium, praseodymium, samarium, gadolinium

Sources: [12–14].

Table 2.
Common uses of rare earth elements in electronic devices.

methods, have been targeted to make e-waste recycling more profitable. Improvements to the mechanization process are fairly straightforward. On the one hand, revisions to shredding and sorting machines have improved the consistency and quality of the materials that are gathered at the preprocessing stage. In addition to this, newly mechanized methods are being developed to extract additional streams of secondary raw materials that were not previously recoverable. The major developments in this arena have been the invention of ways to extract various rare earth elements from electronics. State of the art facilities in Japan and France that can extract rare earths have recently become operational [15, 16]. Continued investment in technologies to recycle rare earths is seen as a strategic priority of industrialized countries, as these materials are essential for technologies related to communications, defense, and other state objectives, yet most mining for these materials takes place in China, a global power that has recently imposed quotas on the quantities that it is willing to sell for export [12, 17–19]. Concerns over the security and stability of the supply of rare earths have driven the development of new mechanized technologies to recover these materials from a wide range of e-waste inputs. Cost effective technologies for recovering secondary neodymium, dysprosium and praseodymium from e-waste are being further developed by U.S.-based recyclers and research institutes [14]. Whether they are sited within the E.U., the U.S., or Japan, these newly operational recycling facilities will require a large quantity of e-waste inputs in order to be profitable. This challenge involves diverting a significant portion of e-waste from landfills, and from the informal recycling industry in less-developed countries.

3. The role of extended producer responsibility in e-waste recycling

Estimates of how much electronic waste is generated globally within a given year vary widely [3, 20]. These estimates are based on the quantity and volume of various electronic items that are purchased in a given year, with consideration to the anticipated life expectancy of that particular item [21]. Surveys of recyclers on the volume of electronics collected can also be factored in, but it is important to note that a significant portion of consumer e-waste is either stored in consumers’ homes or is mixed in with regular household waste and disposed of into landfills [22].

In some instances, data on the amount of e-waste collected for recycling is available, such as in those regions that mandate producers to “take-back” consumers’ unwanted electronics. Such mandates originated as part of the concept of extended producer responsibility (EPR), which holds that the manufacturers of products with hazardous components should bear the logistic and financial burden of recycling or disposing of their products in an environmentally responsible way [23].

While EPR legislation was initially opposed by manufacturers, the increased interest in the strategic importance and potential profitability of the secondary raw materials contained in e-waste (particularly the rare earth elements) has contributed to growing support for such legislation. Variations of EPR “takeback” laws have been put into effect across the globe, including in a number of U.S. states, across the European Union, and across many countries in Asia, Africa and Latin America [24]. These laws signal a potential shift away from electronics recycling taking place primarily in the informal sector, and towards the growth of the formalized e-waste recycling industry.

With a growing number of EPR laws mandating manufacturers to take extended responsibility for the environmentally sound recycling of their products, there has been an increase in the number of pilot projects and public-private partnerships to collect and recycle electronics in ways that are efficient and cost-effective [25]. Some of these projects entail the transport of e-wastes across national boundaries, and have fallen under the purview of the Basel Convention on the Control of the Transboundary Movements of Hazardous Wastes and Their Disposal (the Basel Convention). Over the years, The Basel Convention has convened technical working groups and conducted pilot projects, both of which have resulted in the development of technical guidelines for the handling and management of e-waste [26–28].

Under the purview of the United Nations University, additional pilot projects are being developed to facilitate a globalized e-waste recycling chain that involves labor-intensive dismantling and preprocessing in countries with lower labor costs (e.g., China, India, African countries), and high-tech end-processing in countries with more modern facilities (e.g., the EU countries) [3, 25]. Major recycling corporations, electronics manufacturers, and government officials believe that such partnerships will insure a higher volume of input for large, high-tech smelters and provide access to the secondary raw materials that were previously “dumped” or otherwise retained within the global South countries where informal recycling currently takes place [2, 3].

4. Environmental and human health hazards of electronic waste recycling

The extent to which many of the other materials found in electronics are hazardous to human health and the environment is increasingly well-known. Electronics often contain toxic elements such as lead (Pb), cadmium (Cd), polychlorinated biphenyls (PCBs), polybrominated biphenyls (PBBs) and mercury (Hg) as well as other toxic components such as PVC and brominated flame retardants (BFRs) [29]. **Table 3** presents a list of some of the known hazardous components found in the typical desktop computer (with CRT monitor). This table is an adaptation of material presented by the Silicon Valley Toxics Coalition [30] in their report “Poison PC’s and Toxic TV’s” and toxicity data from Ceballos et al. [31].

Many of the health effects outlined in **Table 3** have been documented in the town of Guiyu, China, where perhaps the greatest portion of the U.S.’s e-waste exports have been deposited historically. Here, almost 80% of children have respiratory problems, and they have an especially high risk of lead poisoning [32]. Neurological, respiratory,

Element	Main applications	Weight (per 60 lb)	Dangers
Lead	Metal joining, radiation shield/CRT, printed wiring board	3.8	Human effects: neurological, blood, kidney damage. Brain damage and poisoning/death for children Accumulates in the environment
Mercury	Batteries, switches/housing, printed wiring board	<0.1	Human effects: long term brain damage and other neurological effects Concentrates through the food chain.
Cadmium	Battery, blue/green phosphor emitter/housing, printed wiring board, CRT	<0.01	Human effects: acute and chronic damage to the kidneys
Plastics (including those containing PVC and BFRs)	Casing, cable coating	22.99	PVC effects: developmental toxin, reproductive toxin, endocrine disruptor. Carcinogenic when burned due to production of dioxins BFR effects: endocrine disruptor, neurotoxin, carcinogen (in humans and animals)

Sources: [30, 31].

Table 3.
A sample of hazardous elements in an older-model PC.

digestive and bone problems are not uncommon among the workers and their families [32]. In addition to these toxicological threats, which include long-term implications for both health and the environment, the threats posed by the recycling of e-waste are even greater when certain recycling methods are employed [33–36]. For example, the informal recycling practice of burning plastic cables to retrieve the copper inside releases dioxins in the air via the burning PVC in the plastic. In more sophisticated operations (most typically found in Asian countries), a process of leaching printed circuit boards with acids (including nitric acid and hydrochloric acid) in order to maximize the amount of gold recovered can cause burns, respiratory and circulatory problems, pulmonary edema and death [2, 4, 36]. The acid stripping leaves behind a toxic residue that oftentimes is disposed of in waterways where it can acidify water and destroy wildlife and vegetation [36–38]. Heavy metal dust can travel to more populous areas and contaminate food supplies and greater populations [39, 40].

There have also been studies on the occupational health and environmental risks associated with high-tech e-waste recycling, with experts noting that much more research needs to be done in this area in order to gain a more accurate assessment of these risks [41–45]. Many of these studies are based on or informed by field research and experiments that measure concentrations of toxic chemicals in the workers, air, and environment around high-tech recycling facilities. There are indications in these studies that technologies such as the introduction of face masks and improved ventilation do decrease occupational exposures to a number of heavy metals and other hazardous chemicals.

In the U.S., a survey of 276 electronic waste recycling facilities was recently completed by the U.S. National Institutes of Occupational Safety and Health (NIOSH) [31]. It is especially relevant to note that this report finds that “most” of the responding facilities rely on manual dismantling, similar to the approach being applied in new and pilot facilities in less developed countries. It is also worth noting that a majority of the responding facilities were certified as environmentally sound either through the industry standard RiOS, the EPA standard R2 Solutions, or the activist standard e-Stewards. Hence, these facilities are likely to represent the “best

case scenario” in electronics recycling. Overall, NIOSH concluded that “e-scrap recycling has the potential for a wide variety of occupational exposures particularly because of the use of manual processes” [31]. One of the primary concerns listed in the report is the potential for exposure to “metal dust” during the process of manual dismantling [31]. Specifically, the report notes that it is unclear whether most facilities have installed proper filtration systems in order to remove metal dust from the air (since the majority of the facilities circulate air within the production area or rely on “natural ventilation”). The report also notes the use of compressed air for cleaning which can heighten exposure to metal dusts. While the initial NIOSH report says that acute exposure to heavy metals such as lead is unlikely, the report notes that “chronic lead poisoning, which is more likely at current occupational exposure levels, may not have symptoms or they may have nonspecific symptoms that may not be recognized as being associated with lead exposure” [31].

Following the publication of the NIOSH report, additional studies of on-site occupational exposures in formal e-waste recycling facilities have been completed. Researchers reviewed 37 studies of the occupational hazards associated with formal e-waste recycling and concluded that, despite clear improvements to worker and environmental health when compared with informal recycling, “formal e-recycling workers and their families may experience unhealthful exposures to metals” [46]. The authors recommend further research “to reduce chemical exposures from formal e-waste recycling,” along with the development of electronics components that are easier to safely disassemble, along with reducing the use of hazardous components in the manufacture of electronics [46]. With e-waste now considered to be the fastest growing stream of hazardous waste in the world, there is an urgent imperative to implement solutions to reduce the risks associated with e-waste recycling [47].

5. Conclusion

The design, production, sale and use of electronics takes place at the global scale. These initial stages in the life cycle of electronics pose a series of hazards to human health and the environment. Similarly, the disposal and recycling of electronics routinely entails the movement of hazardous materials across national borders. Growing government and industry interest in the recovery of secondary raw materials, such as the rare earth elements from e-waste, is leading towards an increase in the development of strategies to increase recycling rates (which currently stand at approximately 20% globally), as well as in the development of formal, mechanized processes for recycling e-waste at the end-processing stage. In some cases, this has entailed the development of enabling legislation such as EPR “take-back” laws, and in other cases this has led to pilot projects that promote partnerships between recyclers in the formal and informal sectors. While there are many additional steps that can be taken in order to ensure that recipients of waste are adequately prepared to manage and recycle them in an environmentally sound manner, progress has been made. As these developments unfold, regulation and oversight will play a decisive role in mitigating the myriad risks to human health and the environment that can result from e-waste recycling.

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Conflict of interest

The authors declare no conflict of interest.

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