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Waste Management Research 2007; 25; 307

DOI: 10.1177/0734242X07076941

Waste Manage Res 2007: 25: 307–318
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Waste Management & Research
ISSN 0734–242X

Electrical and electronic waste: a global environmental problem

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The production of electrical and electronic equipment (EEE) is one of the fastest growing global manufacturing activities. This development has resulted in an increase of waste electric and electronic equipment (WEEE). Rapid economic growth, coupled with urbanization and growing demand for consumer goods, has increased both the consumption of EEE and the production of WEEE, which can be a source of hazardous wastes that pose a risk to the environment and to sustainable economic growth. To address potential environmental problems that could stem from improper management of WEEE, many countries and organizations have drafted national legislation to improve the reuse, recycling and other forms of material recovery from WEEE to reduce the amount and types of materials disposed in landfills. Recycling of waste electric and electronic equipment is important not only to reduce the amount of waste requiring treatment, but also to promote the recovery of valuable materials. EEE is diverse and complex with respect to the materials and components used and waste streams from the manufacturing processes. Characterization of these wastes is of paramount importance for developing a cost-effective and environmentally sound recycling system. This paper offers an overview of electrical and e-waste recycling, including a description of how it is generated and classified, strategies and technologies for recovering materials, and new scientific developments related to these activities. Finally, the e-waste recycling industry in India is also discussed.

Keywords: Environmental, rules, policy, electronic equipment, recycling, wmr 989–2

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DOI: 10.1177/0734242X07076941

Received 3 March 2006; accepted in revised form 17 December 2006

Figures 1, 4 appear in color online: http://wmr.sagepub.com

Introduction

Definition and generation rates of electrical and electronic waste

A broad range of goods is classified as electrical and electronic equipment, including large and small household appliances; Information and technology (IT) equipment including computers, computer games and peripherals; cellular telephones and other telecommunication equipment; portable electronic devices such as portable digital assistants (PDAs), video and audio equipment, including MP3 players and peripherals; and electrical tools (Table 1). Furthermore, many more everyday commodities that were formerly considered electrical equipment, such as refrigerators, are becoming 'electronic' objects through the addition of programmable microprocessors; more than 98% of such devices are embedded in commodities other

Table 1: Major categories of electric and electronic equipments.

Equipment	Units (millions)	Weight (tonnes × 10^3)	% of total
Large household appliances	10	392	43
Small household appliances	15	30	3
IT equipment	22	357	39
Telecommunications	7	8	1
Radio, TV, audio	12	72	8
Lamps	77	12	1
Monitoring and control	8	8	1
Toys	8	8	1
Electrical and electronic tools	6	28	3
Total	165	915	100

Source: UK status report on WEEE (ICER 2000).

than computers, such as household appliances and toys (Hilty *et al.* 2005, Oertel *et al.* 2005).

Once these products reach the end of their useful life, they become e-waste (electronic devices) or WEEE, waste from electrical and electronic equipment. WEEE has been defined as any equipment that is dependent on electric currents or electromagnetic fields in order to work properly, including equipment for the generation, transfer, and measurement of current (Schafer *et al.* 2003). In response to the increasing volumes of WEEE and their potential environmental impacts through various disposal routes, the European Commission has published a proposal in 2002 (EC 2002a) for Directives on Waste from Electrical and Electronic, Equipment (WEEE 2001). The Directive of the Parliament and European Union Council on waste electrical and electronic equipment subdivides WEEE into ten different categories (EU, 2002b).

- Large household appliances (refrigerators/freezers, washing machines, dishwashers).
- Small household appliances (toasters, coffee makers, irons, hairdryers).
- Information technology and telecommunications equipment (personal computers, telephones, mobile phones, laptops, printers, scanners, photocopiers).
- Consumer equipment (televisions, stereo equipment, electric toothbrushes, transistor radios).
- Lighting equipment (fluorescent lamps).
- Electrical and electronic tools (handheld drills, saws, screwdrivers).
- Toys (Playstation, Gameboy, etc.).
- Medical equipment systems (with the exception of all implanted and infected products).
- Monitoring and control instruments.
- Automatic dispensers.

Waste generation

As WEEE extends across a number of industry sectors and is a relatively new focus of environmental concern, accurate data and trends are difficult to ascertain. There is no uniformly accepted definition of WEEE, which has made record-keeping and accounting difficult.

Worldwide, WEEE constitutes one of the fastest growing waste fractions generated, accounting for 8% of all municipal waste (The Economist 2005). The disposal rate of this waste stream is accelerating because the global market for electronics is far from saturated, and the lifespan of electronic goods is becoming shorter, so that obsolete equipment disposal is increasing. For example, for computer central processing units (CPUs), their intended lifespan has dropped from 4–6 years in 1997 to 2 years in 2005 (Culver 2005).

In Europe, the production of electrical and electronic equipment (EEE) is one of the fastest growing business sectors (Cui & Forssberg 2003). Hence, the amount of WEEE will also increase very rapidly. For example, in Europe the expected growth rate of WEEE is at least 3 to 5% per year (Hischier *et al.* 2005). In the former (before May 2004) 15 European Union member countries (EU15), the amount of WEEE produced during 1990–1999 was 3.3–3.6 kg per capita and is projected to reach 3.9–4.3 kg per capita for the period 2000–2010 (EEA, 2003). According to this study (which assessed only five appliances: refrigerators, personal computers, televisions, photocopiers, and small household appliances), these items account for only 25% of the whole WEEE stream of the EU15. Another estimate of the total per capita WEEE generation in the EU15 is 4–20 kg year^{-1} (Widmer *et al.* 2005). Other estimates of total WEEE generation rates for the EU range from 14 to 20 kg per capita (Enviros 2002, Keynote 2003). The range of uncertainty relates mainly to differences in how WEEE is defined.

In 2004, more than 180 million personal computers (PCs) were sold worldwide, and an estimated 100 million obsolete PCs were discarded, with some recycled for the recovery of materials (Hilty 2005). Over 315 million computers entered the WEEE stream in the US (Sayno 2003). According to the US Environmental Protection Agency, over 3.2 million tonnes of WEEE ended up in national landfills in 1997 and the

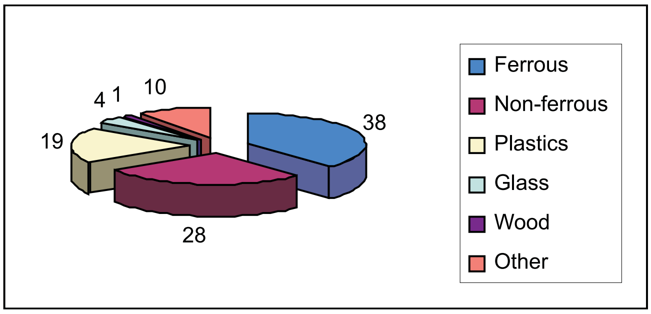

Fig. 1: Materials found in electronic equipment (Zhang & Forssberg 1997).

annual rate is increasing every year (Silicon Valley 2003). In Australia, there are approximately 9 million computers, 5 million printers and 2 million scanners currently in households and businesses, and most of them were replaced in the year 2004 (Department of the Environment and Heritage, 2004–2005). It is estimated that about 130 million mobile phones in the globe were retired in 2005 (Oertel *et al.* 2005).

The per capita waste production in some countries, such as China and India, is relatively very small (estimated < 1 kg per capita per year), but these countries also tend to have some of the fastest growing markets for electrical and electronic equipment because they are far from saturation (Streicher-Portea *et al.* 2005). From 1993 to 2000, the number of PC users in China increased by 1052% whereas the average growth throughout the world was much lower at 181%. During the same period, India showed an increase of 604%. From 1996 to 2002, the number of mobile phone users in China rose to 200 million (LRD 2005).

Waste characteristics

The various elements present in WEEE are shown in Figure 1. It is estimated that about 66% of WEEE by weight consists of metals such as iron, copper, aluminium and gold and non-metals, with other pollutants make up about 34% of the waste. Ferrous metal is the most common material found in electric and electronic components (Morf *et al.* 2006) Data from Ireland show that iron and steel comprise almost half of the total national WEEE waste, which is estimated to be between 25 000 and 30 000 tonnes year^{-1} (WEEE 2001) while non-ferrous metals such as aluminium, copper and some precious metals make up about 13% of their WEEE waste stream (ETC/RWM 2003). Glass accounts for an estimated 5.4% of the total weight of waste from electric and electronic equipment every year (Theisen 2002). Plastics were the second largest component, by weight accounting for approximately 21% of WEEE in Ireland as of 2001 (Wilkinson *et al.* 2001). There is an added danger that some of this plastic is flame retardant and can be damaging to the environment if not disposed of properly.

Hazardous components

WEEE should not be combined with unsorted municipal waste destined for landfills because electronic waste can contain more than 1000 different substances, many of which are toxic, such as lead, mercury, arsenic, cadmium, selenium, and hexavalent chromium. Some of the toxic effects of the heavy metals are given below.

Lead

The negative effects of lead are well established and recognized. Lead causes damage to the central and peripheral nervous systems, blood systems, kidney and reproductive system in humans. The main applications of lead in computers are: glass panels and gasket (frit) in computer monitors (3–8 pounds per monitor), and solder in printed circuit boards and other components.

Cadmium

Cadmium compounds are toxic, they can bioaccumulate, and they pose a risk of irreversible effects on human health (Jarup 1995). Cadmium occurs in certain components such as surface mount devices (SMD) chip resistors, infra-red detectors, and semiconductor chips.

Mercury

Mercury can cause damage to various organs including the brain and kidneys (EU Explanatory Memorandum 1999). Most importantly, the developing fetus is highly susceptible through maternal exposure to mercury (EU Explanatory Memorandum 1999). Mercury is used in thermostats, sensors, relays, switches (e.g. on printed circuit boards and in measuring equipment), medical equipment, lamps, mobile phones and in batteries.

Hexavalent chromium/chromium VI

Chromium VI is still used for corrosion protection of untreated and galvanized steel plates and as a decorative or hardener for steel housings. It easily passes through cell membranes and is then absorbed— producing various toxic effects in contaminated cells (EU Explanatory Memorandum 1999)

Additional harmful substances in WEEE can include arsenic, polychlorinated biphenyls (PCBs), chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), nickel, and asbestos (Ogilvie 2004). Even when present in small amounts, some of these chemicals can be potent pollutants and contribute to toxic landfill leachate and vapours, such as the vaporization of metallic and dimethylene mercury. Furthermore, uncontrolled fires may arise in landfills, releasing extremely toxic dioxins and furans (dioxin-like compounds) into the atmosphere.

Cumulatively, about 500 million PCs reached the end of their service lives between 1994 and 2003 (Matthews *et al.*

1997). Collectively, these machines contained approximately 2 872 000 tonnes of plastics, 718 000 tonnes of lead, 1363 tonnes of cadmium and 287 tonnes of mercury (Puckett & Smith 2002). In 2004, over 315 million computers became obsolete, leaving approximately 1.2 billion pounds of lead, 2 millions pounds of cadmium, and 4 billion pounds of plastics in the waste stream (Puckett & Smith, 2002). Consumer electronics are responsible for up to 40% of the lead in landfills, and about 70% of heavy metals (such as mercury and cadmium) in US landfills come from electronic waste.

Some of the specific components that contain hazardous wastes include:

printed circuit boards
cathode ray tubes
wires and cables
mercury switches
batteries
light generators (e.g., lamps)
capacitors and resistors
sensors and connectors.

Rules and legislation

The laws and policies concerning the proper management of electronic devices are continuing to evolve. Recent regulations have established a permanent funding system for the collection and recycling of cathode ray tubes (CRTs) in the US (IAER 2003). As of 1 January 2005, a nominal fee is collected at the point of sale for all CRTs and is used for CRT recycling activities. The US Electronic Waste Recycling Act of 2003 also includes provisions for reducing the amount of hazardous substances used in electronic products sold in California and a directive to establish environmentally preferred purchasing criteria for state agency purchases of electronic equipment as mentioned in the Act.

The EU defines universal wastes are wastes that under normal circumstances do not present a significant risk to the user, but can pose a threat to the environment if disposed of into a solid waste landfill. As of 9 February 2006, consumer electronic devices (CEDs) will be treated as universal wastes and recycled as per EU legislation. CEDs are devices that contain a toxic component, and the regulations define them as 'any electronic device, including but not limited to, computers, computer peripherals, telephones, answering machines, radios, stereo equipment, tape players/recorders, phonographs, video cassette players/recorders, compact disc players/recorders, calculators, and some appliances (excluding major appliances)'.

Table 2 shows the major hazardous components in WEEE. The directive seeks to contribute to the protection of human health and to the environmentally sound recovery and disposal of WEEE. 'Member States shall ensure that, from 1 July 2006, new electrical and electronic equipment put on the market does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE)' (EC 2002a).

The Basel Convention entered into force on 5 May 1992. The United Nations Basel Convention on the transboundary movement of hazardous waste amterials and their disposal is an international agreement to control the movement and management of hazardous waste across national borders. Article 2 of the Convention defines waste as 'substances or objects which are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law'. The operations which do not lead to the possibility of resource recovery, recycling, reclamation, direct re-use or alternative uses (final disposal). Another part refers the operations that may lead to resource recovery, recycling, reclamation, direct re-use or alternative uses. Thus, under the Basel Convention, recycling is disposal and many secondary raw materials are 'wastes' (Alter 2000).

Similarly, the Basel Convention developed a framework for controls on transboundary movement of such waste. The most prominent example of an international initiative stemming against this type of thinking is the 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. The Convention puts the onus on exporting countries to ensure that hazardous wastes are managed in an environmentally sound manner in the country of import. Apart from Afghanistan, Haiti, and the US, all 164 signatory countries have ratified the convention (Kummer 1995, Secretariat of the Basel Convention 1999).

Table 2: Major hazardous components in WEEE.

Substance	Applications
Mercury	Thermostats, sensors, relays in switches and discharge lamps
Lead	Soldering of printed circuit boards, cathode ray tubes and light bulbs.
Cadmium	Switches, spings, connectors, housings and printed circuit boards.
Hexavalent chromium	Metal coatings for corrosion protection and wear resistance.
Polybrominated biphenyls (PBB) and Polybrominated diphenylethers (PBDE)	Flame retardants in printed circuit boards, connectors and plastic covers.

Table 3: Current tonnages of WEEE collected and recycled in the UK (ICER, 2000).

Type	Arising	Collected	% recycled
IT	357 000	94 600	26
Telecom	8000	4000	50
Video/sound	72 000	3200	4
Large household appliances	392 000	345 300	88

Current collection practices

A variety of collection systems exist in different countries to manage WEEE. In many cases, collection is accomplished via local municipal depots with the support of the original electronics manufacturers (OEMs), who in many countries are already responsible for the collection of the WEEE. Some typical recycling rates in the UK are shown in Table 3 (ICER 2000).

In order for recycling to be successful, the cost of labour, the structure of the economy (including the important informal sector), the existing regulatory framework, and the possibilities and limits of law enforcement must be taken into account in order to find solutions that can improve the situation with regard to environmental impacts, occupational hazards and economic revenue. In order for a recycling system to be sustainable, it must also have the ability to adapt to future changes in the quantity and quality of the waste flows.

The EU Directive on waste from electrical and electronic equipment (WEEE) was based on the premise that improved product design would facilitate recycling and/or disposal of electronic equipment when it outlived its use. The program classified products as shown in Figure 2, and it ahd the following aims.

- Reduce WEEE disposal to landfills.
- Provide for free take-back of end-of-life equipment beginning in August 2005, and in particular, to provide for the establishment of collection facilities and separate collection systems for WEEE from private households; this stipulation involves the establishment of the collection systems for electronic equipment to be deposited/discarded free of charge and also offers free take-back of WEEE from private households when a new product is purchased.
- Provide for the establishment and financing by producers of systems for the recovery and treatment of WEEE, including provisions for placing financial guarantees on new products placed on the market. This stipulation was included to create a financial incentive for manufacturers to improve product design such that less non-recyclable, recoverable, or reusable WEEE is produced. Such reductions could be accomplished through substitution of less hazardous substances; the re-use of components and materials; and incentives from national governments to encourage producers to design equipment that can be easily recycled or refurbished.
- Achieve specified targets for recovery, reuse, and recycling of different classes of WEEE. For example, an annual per capita collection target of 4 kg was set for domestic appliances.

Because of the valuable materials contained in WEEE and programmes such as that outlined in the EU Directive, WEEE recycling has the potential to be an attractive business venture. In many parts of the world, both formal and informal recycling industries to manage the rapidly growing WEEE streams have emerged. Companies such as Boliden (Sweden), WEEE AS (Norway) and Citiraya (UK) are investing in projects to recycle electronic waste materials.

However, in some cases, efforts to divert WEEE from landfills and incinerators have resulted in hazardous dismantling, shredding, burning, exporting, and other unsafe or irresponsible disposal methods. Industrialized countries have made convenient use of the word ‘recycling’ to justify the free trading of hazardous waste materials to the developing countries of Asia, where labor is cheap and health and environmental restrictions are lax. For emerging economies, these materials offer a business opportunity, and entire new economic sectors revolve around trading, repairing, and regaining materials from surplus electronic devices.

The backlogged demand for EEE in developing countries as well as the lack of national regulation and/or lax enforcement of existing laws can also promote the growth of semi-formal or informal WEEE recycling economies that are

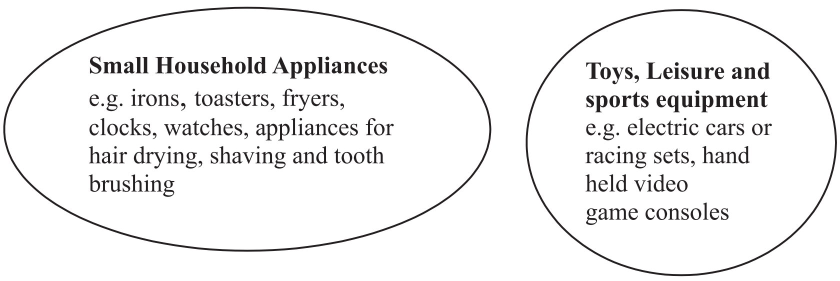

Fig. 2: Classification of small electric and electronic products included in the WEEE.

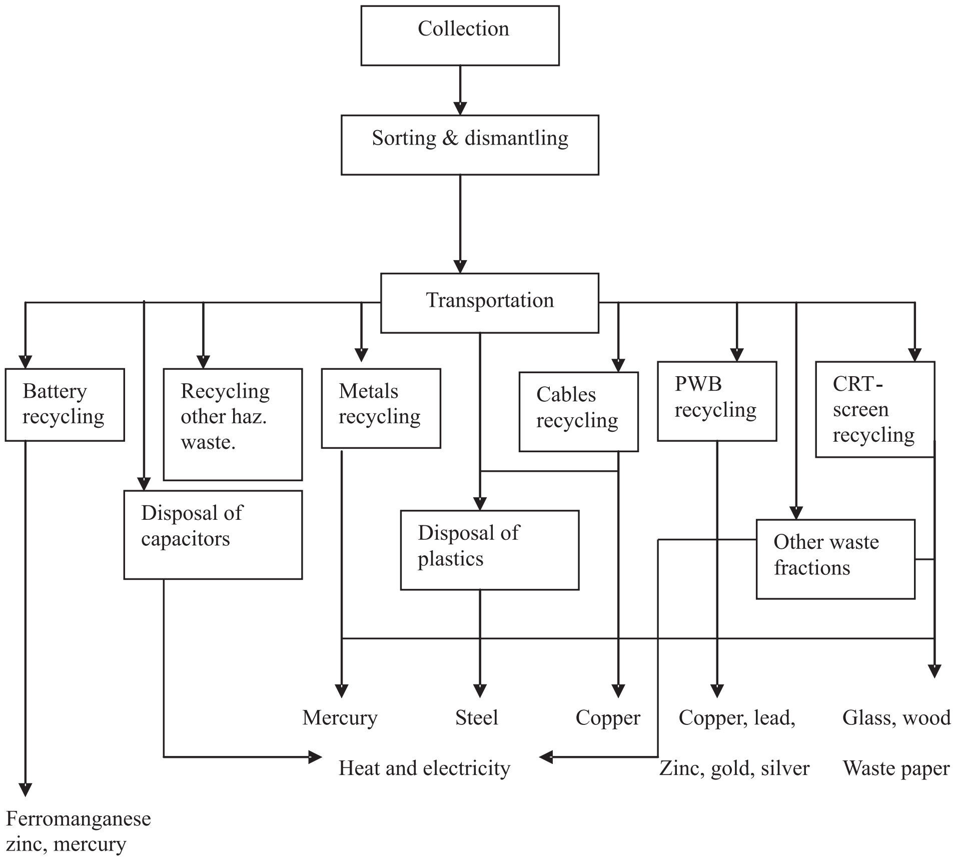

Fig. 3: WEEE take-back and recycling systems: CRT, cathode ray tube; PWB, printed wiring board.

poorly controlled and involve extremely risky techniques. Often the participants in these sectors are not aware of the risks, do not know of better practices, or simply have no access to investment capital to finance profitable improvements (He *et al.* 2006).

Recycling

WEEE recycling is in its infancy, and consumer recognition of the need for recycling is a critical factor in the further expansion of this industry. More than 90% of WEEE is land filled, and in other countries a large fraction of WEEE waste from households ends up in waste incinerators (Anon. 2000).

Many consumers do not immediately discard or recycle unused electronics, since they think that the products retain value. More than 70% of retired CEDs are kept in storage for 3–5 years (USEPA 2000). However, with the rapid development of electronic technologies, the residual value of outdated electronic devices decreases rapidly; both the recovery value of parts and the machine resale value drop rapidly as machines and devices age. Consumers also need to be educated about the effects of such waste on the environment and health, and learn the significance of the recycling symbol that must appear on the packaging of such equipment (a crossed-out wheeled bin).

WEEE represents a challenging recycling problem for several reasons. First, material composition of the products is complex, consisting of low value plastic but also valuable metals and many of the hazardous materials described. Early generation PCs each contained up to 4 g of gold (although levels have decreased to about 1 g per machine today) and 1 tonne of WEEE contains up to 0.2 tonnes of copper, which can be sold for about 500 euros at the current world price (Soderstrom 2004). Second, WEEE includes a widely distributed and diverse set of consumer products with highly variable rates of obsolescence and failure. This means that it is difficult to predict whether particular collection programme types will be cost effective in a given region or how much volume will be generated.

Recycling practices

As WEEE represents a wide range of waste products, the recycling of WEEE varies according to the material content and type of product. A typical schematic of a take-back and recycling flow scheme is shown in Figure 3. Recycling of large household white goods, such as refrigerators and cookers is uncomplicated; however, to recycle smaller, more complex equipment, the development of new infrastructure and technology has become necessary. Some of the most plentiful consumer electronic equipment (brown goods), such as television sets, radios, and video recorders require costly manual dismantling, but the products contain only low-grade precious metals and copper.

Recycling of WEEE can be divided into **three** major stages.

Disassembly/dismantling

Disassembly is the systematic removal of components, parts, a group of parts or a subassembly from a product (i.e., partial disassembly) or the complete disassembly of a product for a given purpose (Gungor 7 Gupta 1998). This is often necessary to isolate hazardous or valuable materials.

Upgrading

WEEE can be regarded as a resource of metals, such as copper, aluminum and gold, and non-metals. Upgrading typically includes two stages: comminution and separation of materials using mechanical/physical and/or metallurgical processing to prepare the materials for refining processes. Precious metal-oriented recovery techniques, such as hydrometallurgy and pyrometallurgy, are becoming less popular whereas mechanical/physical separations of WEEE, which are easier to operate and more environmentally sound, are becoming more prevalent. Other methods to recover materials include incineration and refining, in which metal can be recovered after the more combustible material has been incinerated; and chemical recycling, in which chemical processes are used to remove precious metals such as gold and silver from printed circuit boards. (Zhang & Forssberg 1997).

A mechanical process is ideal for upgrading recycling WEEE because it can yield full material recovery including plastics. Sometimes products will be dismantled to remove the hazardous components and then the remaining material will be granulating and shredded in order to remove the recyclable raw materials such as plastic and ferrous metal. Shredding is often used to produce small even fine-sized particles; usually below 10 mm. (Zhang & Forssberg 1999).

Many of the traditional recycling separation processes, such as screening, shape separation and magnetic separation can be used for particle separation. Eddy current separation, corona electrostatic separation, and jigging are three important processes that have been developed in recycling of automobile scraps, waste cables, and building materials, respectively, and they have been adapted for WEEE recycling as well (Wang & Xu 2003). It is expected that a mechanical recycling process will be developed for upgrading low metal content scraps.

Materials recovery

The major materials in TV and computer are metals, plastics, and glass (Table 4), and the rate at which these materials can be recovered at a given materials recycling facility (MRF) will depend on various parameters such as the size of the facility and the target electronic products (IAER 2003).

Table 4: Summary of material types in remanufactured TVs and computers (unit: wt.%) (IAER 2003).

Materials	TV	Computer
Glass	47.6	24.8
Plastic	14.7	23.0
Printed wiring board	5.6	–
Precious metals	27.1	0.02
Iron	–	20.47
Lead	–	6.3
Aluminum	–	14.17
Copper	4.8	6.93
Others	–	4.3
Total	100	100

Cathode ray tube recycling

CRTs are a major challenge in electronics recycling due to their volume, recycling costs, and disposal restrictions. Recent regulations have established a permanent funding system for the collection and recycling of CRTs in the EU. As of 1 January 2005, a nominal fee is collected at the point of sale for all CRTs. The funds collected are used for CRT recycling activities (Monchamp *et al.* 2001).

CRTs are found in computer monitors, televisions, and other devices, all of which are considered 'universal wastes'. A CRT consists of two major parts: the glass components (funnel glass, panel glass, solder glass, neck), and the non-glass components (plastics, steel, copper, electron gun, phosphor coating). A TV or monitor CRT can also contain from 0.68 to 2.72 kg of lead, which is a toxic metal, and so proper handling of the waste is required to avoid lead contamination of air, soil, and ground water (Eglise & Pierre 2000). CRT glass consists of SiO_2, NaO, CaO, and other components for coloring, oxidizing, and protecting from X-rays (K_2O, MgO, ZnO, BaO, PbO) (Mizuki *et al.* 1997). The two technologies currently available for CRT glass recycling are glass-to-glass and glass-to-lead recycling. To date, the preferred process for the disposal of CRT glass is to recycle it into new CRT glass (ICF Incorporated Fairfax 1999).

An example of the rate of CRT disposal for recycling in Delhi, India is shown in Table 5. The CRT re-gunning process gives the maximum operating margin while the dismantling

Table 5: Summary of the assessment of CRT recycling units in Delhi.

Description	Units received/day
CRTs disposed but operational/day	47
CRTs being re-gunned (320–350 units day^{-1})	350
CRTs rejected for re-gunning/day	544
Total number of monitors disposed/day	941

of rare earth static transformers gives the minimum operating profit per day. CRT that are still working but not operating well will be disposed of (CRTs disposed but operational/day).

Plastics recycling

The unique electrical insulating properties of plastics and their strength, stress resistance, flexibility, and durability make plastics important materials for use in electronics. They are present both internally and on the exterior façade of devices such as telephones, televisions and personal computers. In Western Europe, plastics consumption by the electrical and electronic industry was 2.78 million tonnes in 2002 (Association of Plastics Manufacturers in Europe 2003), and the quantity of plastic waste from these industries increased to approximately 1.13 million tonnes in the year 2005 (Association of Plastics Manufacturers in Europe, 2000).

Removal of paint and coatings

Paint and coatings that are not completely removed in recycled plastics can reduce the strength, resistance, flexibility, and durability properties due to stress concentrations created by these coating materials (Arola & Biddle 2000). Many methods are used to remove coatings, although none is completely satisfactory, and all require that processing conditions be carefully controlled. Furthermore, the degradation that can occur to the plastic substrate during these processes decreases its resale value (Fisher *et al.* 2004).

The chrome from plated plastics can be removed by simple grinding, sometimes assisted with cryogenic methods to enhance the liberation process and to prevent the plating materials from being embedded in the plastic granules. Although cryogenic methods provide good liberation, the actual separation of plastic particles from the paint is problematic (Biddle 1999). Abrasion techniques can be used to remove paint, but they are not suitable for small parts.

Chemical processes are also used, such as solvent stripping, in which the coated plastic pieces are dipped into a solvent. It is an effective process and is used for compact disc coating removal (Biddle, 1999). Aqueous-based paint removal conducted at high temperature is also used to hydrolyse coatings so that they will separate from the plastic. Olefin-based car bumpers can be handled with this technique without degradation to the plastic (Plastic Technology 1994).

Types of plastics

Plastics used in electronics have several important characteristics. The following plastics provide good impact protection: acrylonitrile butadiene styrene (ABS) and high-impact polystyrene (HIPS), which are used in monitors and TVs for CRT protection. Polyphenylene oxide (PPO) has good properties such as high temperature resistance, rigidity, impact strength, and creep resistance. Polyethylene and polyvinyl are excellent electrical insulators. A summary of typical resins used in different equipment is shown in Table 6 (Association of Plastics Manufacturers in Europe, 2000, Minnesota Office of Environmental Assistance 2001, Materials for the Future Foundation 2001).

Table 6: Resins used in electronic products.

Equipment	Resins
TVs	HIPS, ABS, PPE, PVC, PC
Computers	ABS, HIPS, PPO, PPE, PVC, PC/ABS
Miscellaneous	HIPS, ABS, PVC, PPE, PC/ABS, PC

HIPS, high-impact polystyrene; ABS, acrylonitrile butadiene styrene; PPE, polypenylene ether; PVC, polyvinyl chloride; PC, polycarbonate; PPO, polyphenylene oxide; miscellaneous: fax, telephone, refrigerator, etc. (Association of Plastics Manufacturers in Europe 2000).

The major resins in TV sets and computers are HIPS and ABS. The most widely used plastics in the electronic industry are HIPS (56 wt.%), ABS (20 wt.%), and polyphenylene ether (PPE) (11 wt.%) as shown in Figure 4 (Minnesota Office of Environmental Assistance 2001).

Determining which markets can use the plastics found in consumer electronics, the value of the plastics in those markets, and the level and complexity of separation that is necessary to get plastics into usable forms are all problems related to viable recycling of these materials. If recycled plastics are to be used in high-end products, the properties (physical and mechanical) of recovered resins must meet those of virgin resins. In addition, a major concern in plastics recycling is the need to identify and separate the plastic types and identify additives and contaminants. Manufacturers are beginning to recognize that it may be necessary to reduce the number of plastic resins used in electronics to make recycling of electronics plastics feasible. For example, the automotive industry is reducing the plastic grades it uses from 100 to seven or eight types, and of these, only three or four will be used in greater volume (Biddle 1998).

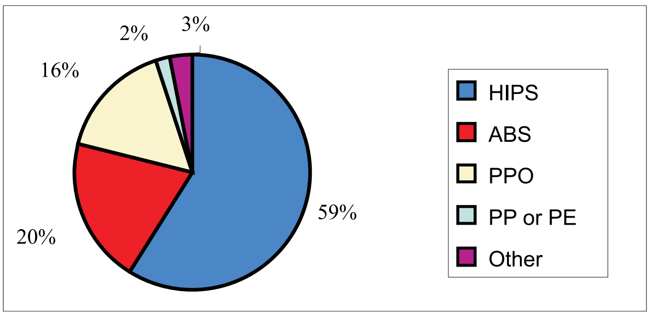

Fig. 4: Manufacture of plastic from organic compounds. HIPS, high-impact polystyrene; ABS, acrylonitrile butadiene styrene; PP, polypenylene; PE, polyethylene; PPO, polypropelene oxide.

It is considering mandates for lower levels of the plastics of concern in manufacturing and assembly to avoid chlorinated or brominated flame-retardants. Instead, non-halogenated flame-retardants or equipment designed with a self-extinguishing base will be recommended.

Two of the most common plastic resins used in electronics are thermosets and thermoplasts. Thermosetting plastics (thermosets) are polymer materials that cure, through the addition of energy, to a stronger form. The energy may be in the form of heat (generally above 200°C), through a chemical reaction (two-part epoxy, for example), or irradiation.

Thermoset materials are generally stronger than thermoplastic materials, and are also better suited to high-temperature applications. They do not lend themselves to recycling like thermoplastics, which can be melted and re-moulded.

- Bakelite, a phenol formaldehyde resin (used in electrical insulators and plastic wear).
- Epoxy resin (used as an adhesive and in fibre-reinforced plastics such as glass-reinforced plastic and graphite-reinforced plastic).

A thermoplastic is a material that is plastic or deformable, melts to a liquid when heated and freezes to a brittle, glassy state when cooled sufficiently. Most thermoplastics are high molecular weight polymers whose chains associate through weak van der Waals forces (polyethylene); stronger dipole–dipole interactions and hydrogen bonding (nylon); or even stacking of aromatic rings (polystyrene). Thermoplastic polymers differ from thermosetting polymers (Bakelite; vulcanized rubber) which, once formed and cured, can never be remelted and remoulded. Many thermoplastic materials are addition polymers; e.g., vinyl chain-growth polymers such as polyethylene and polypropylene.

Precious metals recovery

Investigations to date have mainly focused on the recovery of precious metals from PC scrap and printed circuit board scrap (Brandon *et al.* 2001 Kindesio 2002). However, it is important that recycling of the electronic scrap that contains low-grade precious metals be further investigated.

Precious metals such as gold, silver, palladium and platinum are recovered in a refinery. After copper electrolysis, the anode slime is leached by pressure. The leach residue is then dried and, after the addition of fluxes which act as catalysts to improve the reaction faster, smelted in a precious metals furnace. During smelting, selenium is recovered. The remaining material, primarily silver, is cast into a silver anode. In a subsequent high-intensity electrolytic refining process, a high-purity silver cathode, and anode gold slime are formed. The anode gold slime is then leached, and high-purity gold, as well as palladium and platinum sludge, are precipitated.

Recycling of WEEE in India

India, with over 1 billion people, is the second most populous country in the world and one of the major WEEE-producing countries in the world (World Bank 2004). Moreover, India is one of the fastest growing economies of the world and there is an increasing domestic demand for consumer durables. The growth in PC ownership per capita in India between 1993 and 2000 was 604%, compared to a world average of 181%. As a result, the total PC base during this period has grown from an estimated 450 000 to 4 200 000 (WITSA 2002).

The Manufacturers' Association of Information Technology (MAIT 2004) published data that give an overview of PC market penetration over the period 1996–2004 for all of India and for Delhi (Table 7).

Table 7: Overview of PC market from period 1996–2004: N.B. all numbers are thousands.

Year	PCs/1000	Population	India			Delhi		
		(× 10^3)	PC base (× 10^3)	Sales (× 10^3)	Growth (× 10^3)	Base (× 10^3)	Sales (× 10^3)	Growth (× 10^3)
1996	0.7	934 300	650	600		160	150	
1997	1.4	949 900	1330	800	680	330	200	170
1998	2.1	965 600	2030	1000	700	510	250	180
1999	3.1	981 300	3040	1400	1010	760	350	250
2000	4.5	997 000	4490	1740	1450	1120	440	360
2001	6.3	1 012 400	6380	1800	1890	1600	450	470
2002	8	1 027 600	8220	2430	1840	2060	610	460
2003	9	1 043 500	9390	3300	1170	2350	830	290
2004	11	1 060 000	11 660		2270	2920		570

Source: For all these figures a constant share of 25% for Delhi is assumed, rounded off at a 10 000 (MAIT 2003, 2004 and Census of India 2001).

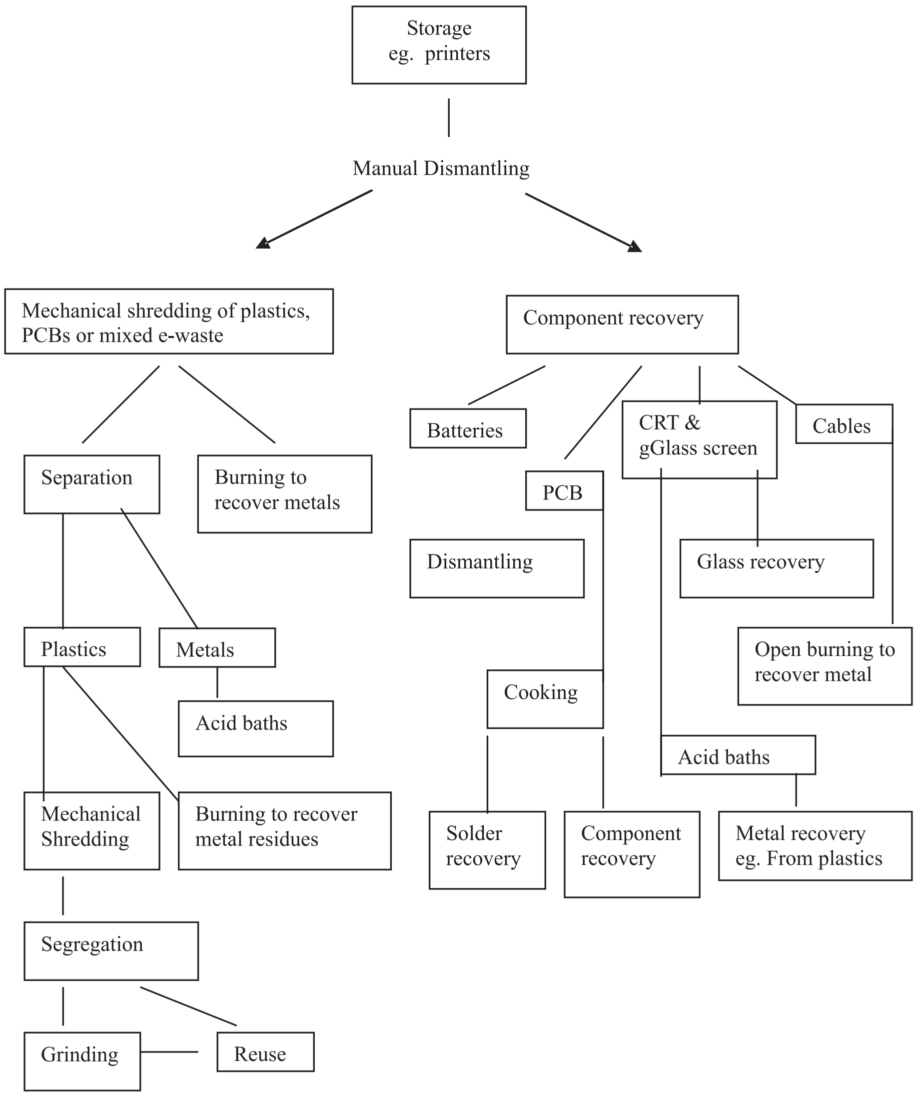

Fig. 5: Different stages of WEEE recycling processes in India: CRT, cathode ray tube; PWB, printed wiring board.

Table 8: Total number of scrap PCs entering Delhi's dismantling/recycling market.

Scrap PCs in Delhi (2003)	Obsolete after years	
	5	7
Local PCs	250 000	150 000
Imported PCs	133 000	133 000
Grand total	383 000	283 000
Total number of PCs dismantled/day	1277	943
Scrap mark up (ratio imported/local)	53%	89%

PCs are recycled in India. Field surveys show that for about 300 days of the year, two truckloads of scrap PCs arrive daily in Delhi, which translates to about 133 000 units and 3600 tonnes arriving per year (assuming an average PC weighs about 27 kg) (Agarwal *et* al. 2005) (Table 8). For an assumed obsolescence time of 7 years, for instance, the quantity of locally produced PC scrap is almost doubled by imports (+ 89%) (MAIT 2004, Empa Survey 2004).

Different stages of WEEE recycling processes sampled in India are given in Figure 5, which shows a flow chart of the recycled process in India.

Conclusions

Proper management of WEEE is a concern that has been recognized by both government agencies and the general public. In order to accelerate the rate at which proper processing and management methods are employed, timely regulatory and legislative policies and procedures are needed. EU legislation is anticipated that will require cost-effective and environmentally sound WEEE recycling technologies for the electronics industry along with greener product design and production concepts. It is important that these requirements be addressed in a proactive manner.

To properly separate, process and isolate the wastes, they must be well-characterized, which is challenging because they tend to be quite heterogeneous and complex in terms of the type, size, and shape of components and materials. Therefore, continued in-depth and multidisciplinary study is needed to understand this special waste stream. One important direction for future research would be to project the flows of WEEE worldwide and quantitatively and qualitatively assess their social, environmental, and economic costs. To develop a mature recycling industry for electronic wastes, the dynamics of WEEE generation and markets need to be better understood. The development of a stable recycling industry will depend in part on stable material supplies.

From a policy perspective, further research into the applicability, effectiveness, and efficiency of various processes and equipment for managing WEEE is needed. Current technologies are not particularly cost-effective, and to date, many aspects of recycling depend on manual operations. In addition, existing methods are limited in their ability to handle complex products such as CRTs and PCs that contain a wide variety of materials. Finally, it is also necessary to arouse and enhance public awareness regarding environmental protection by publicity and education to guide consumer preferences to support products that are produced with and ultimately generate little hazardous or solid waste. As some of the issues related to electronic wastes are better understood and quantified, the findings could provide a basis for modeling different intervention options and predicting their effects.

Acknowledgements

The authors thank Professor Helene Hilger, for editing our manuscript and the Director, CECRI, Karaikudi, India.

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