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Recycling of WEEE plastics: a review

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Abstract Electric and electronic equipment (EEE) is swiftly growing in volume, level of sophistication, and diversity. Also, it evolves briskly, moved by innovation and technical change, and draws on numerous and at times rare resources. Waste EEE (WEEE) has evolved into an important societal problem. Recycling and treating WEEE implies occupational as well as environmental hazards that are still incompletely documented. Still, second hand EEE has been exported and treated in Africa, China, and India in a precarious informal context. In developed countries, EEE recycling has been sustained by a wide range of initiatives and motives, such as sustainability, creating jobs, and the value of precious or rare metals. Current EU Directives require a steep reduction of WEEE plastics (WEEP) going to landfill. Mechanical, thermal, and feedstock recycling of WEEP are analysed and some options confronted. Plastics recycling should be weighed against the eventual risks related to their hazardous ingredients, mainly legacy brominated fire retardants and heavy metals. Another paper is related to a somewhat similar problem, yet involving a different mix of plastics: recycling plastics from automotive shredder residue.

Keywords Brominated fire retardants · e-waste · Electronic scrap · Heavy metals · Plastics recycling · Waste electric and electronic equipment (WEEE) · WEEE plastics (WEEP)

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Introduction

An average family in the affluent world during the *Golden* 1960s possessed only few electric devices: typically a radio, a black and white television set, refrigerator, vacuum cleaner, washing machine, and disc player. Thirty years later, rapid evolution and wide availability justified the statement: "With the proliferation and staggering rate of technological development of electronic equipment, the question of how to dispose of it is becoming increasingly urgent" [1].

Today, the production of electrical and electronic equipment (EEE) is still one of the fastest growing global manufacturing activities and its turnover even exceeds that of car manufacturers. Fast growth also results in creating more waste electric and electronic equipment (WEEE, electronic or e-waste). The amounts put on market (PoM) are recorded with fair precision, as are the amounts of WEEE recycled in each EU country (Eurostat) or Japan [2]. In contrast to most other waste, there may be considerable time lag between the decommissioning of equipment and its eventual reporting to the stream of e-waste. Thus the amounts reused, remanufactured, exported, or reported to municipal solid waste (MSW) are uncertain (cf. the Eurostat data in Tables 7, 10). Small e-devices (s-WEEE) [3], such as an electric toothbrush, hairdryer, or handy phone often report to MSW. Metal rich e-waste is sold for its metal value, or even stolen for it.

Obsolescence triggers fast *substitution* of both telecommunication and information technology (IT) materials; cathode ray tube monitors (CRT) are rapidly replaced by liquid crystal display (LCD) and plasma monitors, just as in the 70s colour television (TV) supplanted black and white, increasing the amount of waste to dispose of. There are at least some 1000 different substances in e-waste. Close intermingling of materials, as well as their use in minute quantities make it quite impractical to separate and sort these streams entirely; moreover, there is enormous variety in e-waste and its composition. E-waste also contains hazardous pollutants, including heavy metals, such as mercury, lead and cadmium, condensers containing polychlorinated biphenyls (PCBs), or brominated fire retardants (BFR), e.g. in casings and printed circuit boards (pcbs).

Definitions

WEEE is an electrically powered appliance that no longer satisfies the current owner for its original purpose [4]. In each nation WEEE is described differently, by means of inclusive lists and/or legal definitions. The Swiss Ordinance on the return, the taking back and the disposal of electrical and electronic equipment (1998) discerned 4 generic groups [5]:

- Electronic appliances for entertainment.
- Appliances forming part of office, communication and IT.
- Household appliances.
- Electronic components of the (above) appliances.

In 2004, it was amended to match the EU Directive's classification featuring ten categories (Table 1) of e-waste that should not be eliminated together with ordinary waste, i.e. MSW (Fig. 1). An Indian classification system is limited to 6 classes, whereas the Japanese system started smaller in scope, with TVs, refrigerators, washing machines, air conditioners and personal computers or PCs.

Individual appliances differ markedly in size, weight and composition; hence, citing typical values does not make much sense, unless the type of appliance and its period of production are given. Lighting bulbs are largest in number. Categories 1–4 in Table 1 account for nearly 95 % of the weight amount generated (93.3 % in 2010). Recycling of WEEE is important, not only to reduce the amount of waste requiring treatment, but also to promote the recovery of valuable materials as well as the responsible elimination of its intrinsic hazardous and environmentally objectionable components and compounds.

WEEE is mainly composed out of ferrous and nonferrous metals (Table 2); next comes WEEE plastics (WEEP). The amount and internal composition of WEEP also depends on the type of appliance (Tables 3, 4; Figs. 2, 3). Managing either the disposal or recovery of plastics is important from environmental, occupational and economic perspectives: WEEP contain hazardous substances and may give rise to toxic emissions during improper recycling or elimination, or else to high processing costs in case of responsible treatment. This delicate balance between values and liabilities leads to questions such as: who will pay for responsible treatment and how to deal with *cherry*

Fig. 1 The WEEE symbol (implying no elimination via MSW!)

Table 1 WEEE categories according to the EU Directive on WEEE [6]

No.	Category	Label
1	Large household appliances	Large HH
2	Small household appliances	Small HH
3	IT and telecommunications equipment	ICT
4	Consumer equipment	CE
5	Lighting equipment	Lighting
6	Electrical and electronic tools (with the exception of large-scale stationary industrial tools	E&E tools
7	Toys, leisure and sports equipment	Toys
8	Medical devices (no implanted and infected products)	Medical equipment
9	Monitoring and control instruments	M&C
10	Automatic dispensers	Dispensers

Table 2 Plastic concentration in WEEE [7]

Equipment category	Ferrous metals (%)	Non-ferrous metals (%)	Glass (%)	Plastics (%)	Other (%)
Large household appliances	61	7	3	9	21
Small household appliances	19	1	0	48	32
IT equipment	43	0	4	30	20
Telecom	13	7	0	74	6
TV, Radio, etc.	11	2	35	31	22

Table 3 Typical applications of plastic polymers in EEE [8]

Polymer	Application
ABS	Housings and casting of phones, small household appliances, microwave ovens, flat screens and certain monitors
	Enclosures and internal parts of ICT equipment
PS (HIPS)	Components inside refrigerators (liner, shelving)
	Housings of small household appliances, data processing and consumer electronics
PC	Housings of ICT equipment and household appliances
	Lighting
Epoxy resins	Printed circuit boards (pcbs)
PP	Components inside washing machines and dishwashers, castings of small household appliances (coffee makers, irons, etc.)
	Internal electronic components
PPO (blend HIPS/PPE)	Housings of consumer electronics (TVs) and computer monitors and some small household appliances (e.g. hairdryers)
	Components of TV, computer, printers and copiers
PC/ABS	Housings of ICT equipment and certain small household appliances (e.g. kettles, shavers)

Table 4 Main polymers used in the manufacture of the most common WEEE items collected [9]

WEEE item	Polymer composition
Printers/faxes	PS (80 %), HIPS (10 %), SAN (5 %), ABS, PP
Telecoms	ABS (80 %), PC/ABS (13 %), HIPS, POM
TVs	PPE/PS (63 %), PC/ABS (32 %), PET (5 %)
Toys	ABS (70 %), HIPS (10 %), PP (10 %), PA (5 %), PVC (5 %)
Monitors	PC/ABS (90 %), ABS (5 %), HIPS (5 %)
Computer	ABS (50 %), PC/ABS (35 %), HIPS (15 %)
Small household appliances	PP (43 %), PA (19 %), ABS-SAN (17 %), PC (10 %), PBT, POM
Refrigeration	PS&EPS (31 %), ABS (26 %), PU (22 %), UP (9 %), PVC (6 %)
Dishwashers	PP (69 %), PS (8 %), ABS (7 %), PVC (5 %)

picking, i.e. the selective removal of valuable parts from the bulk?

Metals

The recovery of precious metals (Ag, Au, Platinum group metals) used to be a major driver for recycling pcbs: precious metals make up more than 70 % of the value of cell phones, calculators, and pcbs, and still contribute 40 % to that of TV boards and DVD players. Next comes copper, zinc and other metals.

Some metals are used for very specific purposes, i.e. indium in LCD screens, gold, silver and palladium in non-oxidising contacts of pcbs, silver in radiofrequency identification antennas. A survey of such applications is given in [11]. Lithium, gallium, tellurium, germanium, ruthenium all are classified as strategic metals [12]. The problem of losing rare or precious elements has spurred special attention, mainly in Japan [13].

EEE production consumes more than half of all ruthenium and indium produced and >30 % of the elements Ag, Cu, Sb, Sn (Table 5). Their recovery involves either hydrometallurgical or pyrometallurgical methods. The first group of processes is based on acid or caustic leaching or extraction, followed by stepwise separation. The second group is based on oxidation/reduction processes and on the partitioning of elements between collector elements, such as lead or copper, and slag. Table 5 shows (a) the annual production, (b) the consumption by EEE production, and (c) the ratio *b*/*a*, in wt%.

This rich composition explains the large interest of some specialised enterprises (e.g. Boliden, Cumerio, Noranda, Umicore) in processing WEEE in metallurgical plant. Pcbs contain more than 20 % of Cu; shredded, they could be fed directly into copper or lead smelting plant. The emission problems (dioxins) in these smelters were mastered already a decade ago [15–18].

Batteries are outside the scope of this survey and subject of a separate Directive [19]. Small batteries are collected to prevent pollution and recycle metals. Lead batteries feature injection-moulded PP boxes that are either recycled as resins, or used as fuel in the blast furnaces recovering lead and antimony alloys.

Plastics

Plastics are important as an electric and/or thermal insulator and as a lightweight, easily formable structural component. Part of these structures is strengthened and stiffened by charging the resin with reinforcing fibres. Thermosets show a high stability and play an important role.

The share of plastics in EEE has continuously increased from about 14 % (1980) to 18 % in 1992, and 23 % in 2005. Their part in European WEEE was estimated at 20.6 % (2008). Supposing that the WEEE Forum members collected and treated about 1.5 M tonnes of WEEE in 2008, they salvaged or disposed of some 300,000 tonnes of plastic waste [20], forming, however, a complex mix. Even small appliances can contain up to six different plastic resins (Table 3). WEEP contains numerous different resins, such as styrenics (PS, HIPS, ABS, SAN), polyolefins (HDPE, LDPE, PP), engineering plastics (PC, POM, PUR, PA, and PVC), and thermosets. Before processing, plastics are always compounded with additives such as stabilisers (thermal and UV), antistatic agents, flame retardants,

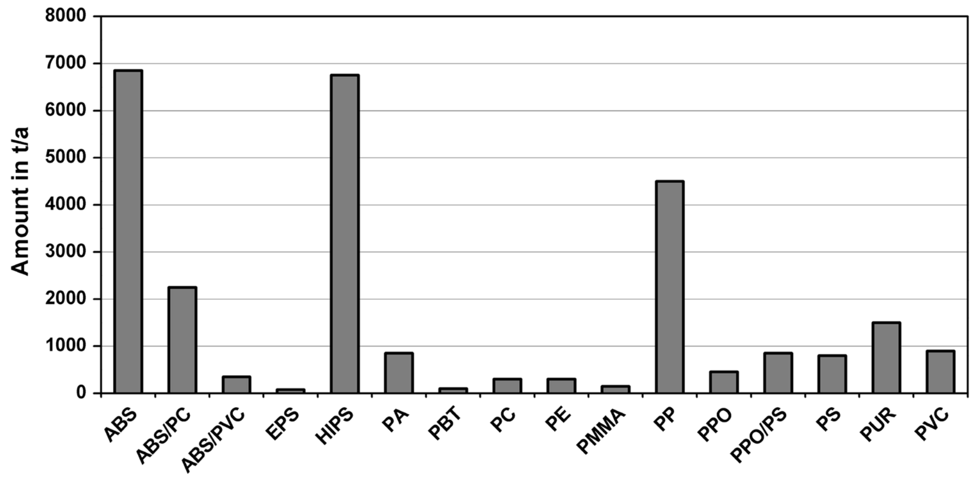

Fig. 2 Annual flows of plastic types in Swiss WEEE (2007) [10]

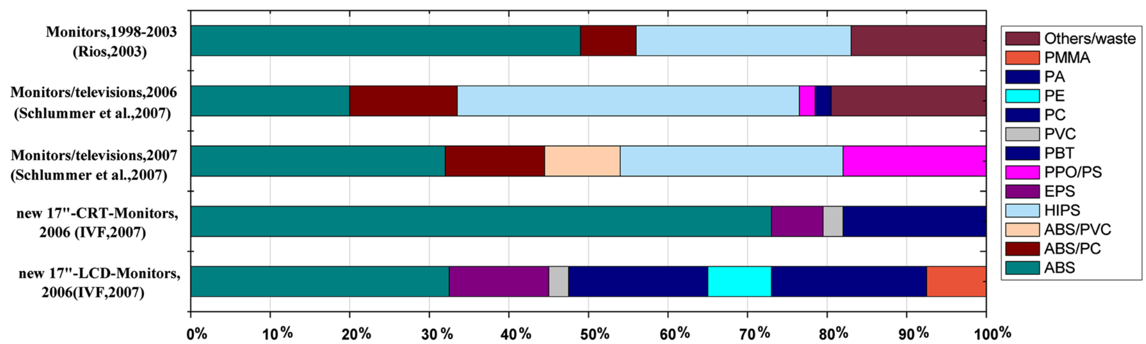

Fig. 3 Shares of plastic types in PC monitors, according to different sources [10]

Table 5 Annual production, consumption by EEE production, and their ratio [14]

Metal	Annual production, tonnes (2006)	Demand for EEE, tonnes/years	Demand/ production (%)
Silver	20000	6000	30
Gold	2500	300	12
Palladium	230	33	14
Platinum	210	13	6
Ruthenium	32	27	84
Copper	15000000	4500000	30
Tin	275000	90000	33
Antimony	130000	65000	50
Cobalt	58000	11000	19
Bismuth	5600	900	16
Selenium	1400	240	17
Indium	480	380	79

colourants, pigments, plasticisers, fillers, reinforcing glass or carbon fibres. Most concerns relate to the possible presence of brominated flame retardants (BFRs) and of heavy metals, whether intrinsic or extraneous, introduced as impurities by prior processing of WEEE.

Mechanical/physical processing will likely play a vital role in upgrading WEEE. Plastics-rich streams (>95 % plastics by weight) are obtained best by manual dismantling, yet this gives rise to high labour cost. After removal of all hazardous substances, the alternative is shredding and multistep mechanical separation. An inevitable consequence is the embedding of foreign matter into the plastic matrix. Economic pressure may lead the shredder operator to optimise towards high metal recovery, resulting in WEEP unsuitable in size for further recycling.

The principal plastics group of WEEE are styrenics. Detailed data on the composition of plastics from WEEE are provided in, e.g. various studies of EMPA. Table 4 describes the composition by polymer of the main WEEE items collected. Figure 2 gives the total plastics' streams in Switzerland (2008). The following plastic types dominate different WEEE product categories (in order of decreasing share):

- Consumer electronics, including television sets: HIPS and ABS.
- Information technology devices: ABS, HIPS, ABS/PC and PPO/PS.

- Large electrical appliances: PP, PUR, ABS, PS and HIPS.
- Small electrical appliances: PP, HIPS and ABS.
- Cooling appliances: ABS and HIPS, PUR, PP and PVC.

In an EMPA study, WEEP fractions were analysed for four heavy metals (cadmium, hexavalent chromium, mercury and lead) and those brominated flame retardants (PentaBDE, OctaBDE, DecaBDE, DecaBB) that are regulated (i.e. phased out) by the RoHS Directive. Also other flame retardants (HBCD, TBBPA), total bromine, total phosphorus, and antimony were analysed. All fractions contained in quantifiable amounts at least one substance regulated by the RoHS Directive, indicating the presence of legacy additives. The final destination of such waste should be located in identifiable landfill cells, with a high level of environmental protection and a prospect for later landfill mining [20].

Legal basis

The two relevant Directives on WEEE [21, 22] and restriction of hazardous substances (RoHS) initially started during their preparatory stage as a single Directive, aiming at reducing the environmental impact of WEEE. Taking into account the waste hierarchy (Fig. 4), there was a need to address both start and finish of the product life cycle. The WEEE Directive 2002/96/EC covers both treatment and recycling of WEEE. It encourages reuse and recycling and reducing the amount of WEEE to discard. The Directive requires producers to pay for at least the collection of their products at end-of-life from central points, and to meet targets for reuse, recycling and recovery. Attaining such goals is supported even before production starts by design for recycling and design for environment. The RoHS Directive deals with hazardous substances (see further).

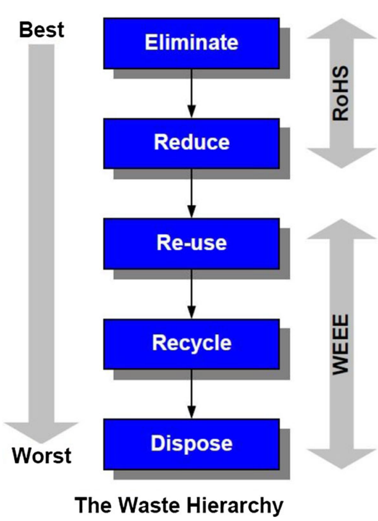

Fig. 4 The waste hierarchy in the product life cycle

Country reports

Originally, e-waste was chiefly generated in countries of the Organisation for Economic Cooperation and Development (OECD), with almost saturated internal markets (new acquisition = scrapping an old appliance). In newly industrialising countries the EEE market penetration is still low, yet showing faster growing rates, so that large amounts of domestic e-waste will eventually emerge. Several authors described the status of e-recycling in countries such as Taiwan [16], Korea [23], the USA [24, 25], China [26, 27], Scotland [28], Greece [29], Germany [30], Switzerland [31], Sweden [32] and India [7, 33].

In emerging countries, informal backyard recyclers ignite e-waste in order to recover metals from ashes, creating considerable health problems to the workers and the community surrounding the workplaces. Leaching liquors pollute their surroundings with heavy metals. Both formal recyclers and Greenpeace blame these procedures; other parties such as EMPA also try and correct them [34].

Europe

Early recycling of WEEE was largely based on the experience of few European Countries, where various organisations were managing voluntary take-back and recycling systems. At present, EEE producers have become legally responsible for financing collection and recycling. The national associations actively managing WEEE take-back systems in 2002 set up a WEEE executing forum, then including associations from Austria, Belgium, the Netherlands, Norway, Sweden, and Switzerland.

The E.U. Directive has been transposed into national legislation, including prescriptive requirements such as collection per capita, treatment standards, and recovery targets. The original Directive Targets could easily be met by recycling metal, glass and other materials; therefore, the plastic parts were not an immediate issue. Plastics treatment ought to be encouraged by implementing both the landfill directive (ban on dumping high calorific waste plastics) and the incineration directive, encouraging the incineration of such waste for energy recovery [35].

Table 6 shows a partial listing of numerous stakeholders from Industry Associations, Authorities, or NGOs compiled during this literature survey. Ironically, the ambitious initiatives announced by the E.U. in the 90s at first had a dampening effect on initial developments, creating a

Table 6 Partial list of stakeholders

Association of plastic manufacturers in Europe (APME).	Electronics resellers association international (ERAI)
The Basel action network (BAN).	Green computing, green IT
British plastics federation's recycling group (BPFRG)	Greenpeace ICT sustainability,
Bromine science & environmental forum (BSEF)	Identiplast
Bureau of international recycling (BIR).	Industry council for electronic equipment recycling (ICER)
European association of plastics recycling and recovery organisations (EPRO)	Institute of scrap recycling industries (ISRI),
European brominated flame retardants industry panel (EBFRIP, Brussels)	International network for environmental compliance and enforcement (INECE),
European committee of domestic equipment manufacturers (CECED).	International symposium on feedstock recycling (ISFR). Biannual Global Conference
European electronic recyclers association (EERA).	Orgalime (Organisme de Liaison des Industries Métalliques Européennes),
European flame retardants association (EFRA).	Plastic waste management Institute, Japan.
EMPA (Eidgenössische Materialprüfungs- und Forschungsanstalt).	Plastics Europe
European electronics recyclers association (EERA).	RECOUP
EuPC (European plastics converters)	Solving the e-waste problem (StEP),
EuPR (European plastic recyclers)	Sustainable electronics initiative (SEI)
European recycling platform (ERP).	VECAP
	WEEE & ELV Working group,
	WEEE forum

pernicious climate of uncertainty. Still today, E.U. requirements are internally conflicting: the desire of promoting plastics recycling is contested by the obligation of eliminating all legacy additives.

Table 7 shows the WEEE recovery in European countries in 2010, in amount per category. Germany recycled the largest amount of WEEE, i.e. 736,321 metric tonnes (Mg), followed by France and Sweden with 356,658 and 148,250 Mg, respectively. Large household appliances are the largest group in recycled WEEE (45.5 % of the total WEEE recycled), followed by consumer electronics and IT and telecommunication equipment, at ca. 20 % each [36].

WEEE recovery in Europe countries in 2010 (Mg). Derived from EUROSTAT [36] and rounded to 1 Mg.

Early initiatives

Some countries were early to address WEEE issues, e.g. Japan, Switzerland, Sweden, the Netherlands, Germany. Also some corporations showed pro-active involvement, e.g. Hewlett-Packard (HP). Non-Governmental Organisations were right in reproving exports of WEEE, at times disguised as EEE [37].

Japan

Already in the 50s and 60s Japan became a major producer of electronics, cameras, and IT. In the 70s, the first initiatives to recycle WEEE were launched, yet their dismantling was too costly. In 2001, recycling of WEEE became legal requirement under the Home Appliance Recycling Law and the Law for Promotion of Effective Utilisation Resources. A recycling rate of 50–60 % was required, so there was no need for recycling plastics. However, by 2008 the recycling rate was to be raised 80–90 %, implying that plastics must be recycled. Hence, developing recycling technology for plastics, also those containing BFRs, and to prepare for reviewing the legal system, in cooperation with associations representing the manufacturers of BFRs, EEE and plastics became important [13, 38, 39].

China

Today, China produces a significant share of the global EEE output [27]. In 2006, China generated 1.7 M tonnes of e-waste, or 1.3 kg per capita. Moreover, there was huge inflow of e-waste, treated at first by the informal sector [13, 39, 40], later by regulated enterprise. Soon, e-waste became a major environmental concern, because of the crude treatment used during dismantling and processing and the associated release of toxic chemicals such as PBDEs [41]. Elevated concentrations of PBDEs in the environment around e-waste sites, as well as in humans have been reported [42, 43]. Open burning sites, combustion residues, ash, soils and sediments all are seriously contaminated by crude treatment of e-waste, e.g. in Taizhou (Zhejiang Province), or Guiyu and Chendian (Guangdong Province), where increased pollutant levels, in particular dioxins [44], PCB [45], Pb, Cd, Cu [46], Cr [47], PBDE [48] and PAH [49] in body fluids have been reported.

Table 7 WEEE recovery in Europe Countries (metric tonne, 2010) [36]

	LHH	SHH	IT&TE	CE	LE	GDL	EET	TLSE	MD	MCI	AD	Total
Austria	28426	5411	14680	14131	883	797	1600	57	181	147	60	66371
Belgium	42578	7675	15625	20219	1158	1162	1836	182	260	97	1101	91892
Bulgaria	26237	2803	2245	2654	207	218	1016	178	100	326	190	36173
Cyprus	1407	111	310	0	0	0	32	9	0	0	0	1869
Czech Republic	23704	2385	9845	11102	284	682	604	159	79	100	36	48980
Denmark	29975	3424	17464	22280	5	636	647	618	48	312	7	75416
Estonia	2215	405	1113	1412	24	55	136	15	/	14	0	5389
Finland	25651	1107	7415	10863	104	766	259	83	40	92	186	46567
France	201006	17524	47705	80194	166	3454	4075	792	323	876	543	356658
Germany	235184	69423	205214	183780	754	9708	21496	3178	2648	1172	3766	736321
Greece	28559	1766	7475	7033	180	65	59	168	127	46	120	45598
Hungary	18325	2362	4453	8764	169	563	491	39	10	34	26	35236
Ireland	20449	2589	3443	6532	804	327	871	40	232	328	727	36342
Italy	/	/	/	/	/	/	/	/	/	/	/	0
Latvia	1723	255	473	471	134	160	179	91	69	49	27	3629
Liechtenstein	/	/	/	/	/	/	/	/	/	/	/	0
Lithuania	3910	438	869	713	92	141	415	77	64	252	14	6983
Luxembourg	1985	359	732	968	98	60	124	19	/	4	0	4349
Netherlands	59849	6684	19889	26789	1197	1512	1696	460	170	73	2765	121084
Norway	41583	6774	14290	15530	6076	898	8839	386	503	1879	177	96935
Poland	47435	7513	8777	11688	2218	3390	5907	1345	96	310	17	88694
Portugal	23947	3855	6710	4012	573	/	375	102	270	335	370	40549
Romania	13119	770	5526	3186	53	107	542	46	/	183	72	23604
Slovenia	3378	415	2165	784	48	109	72	12	11	20	34	7049
Spain	66418	3827	17908	21117	1842	966	1120	2128	777	264	129	116496
Slovakia	10993	1468	2930	2275	614	294	479	27	106	111	79	19374
Sweden	68414	8114	29371	35585	2167	1956	1261	571	475	84	252	148250
United Kingdom	/	/	/	/	/	/	/	/	/	/	/	0
Sum of the column	1026467	157456	446625	492082	19850	28026	54131	10779	6589	7106	10699	2259808
Idem, in (%)	45.42	6.97	19.76	21.78	0.88	1.24	2.40	0.48	0.29	0.31	0.47	100

LHH large household appliances, *SHH* small household appliances, *IT&TE* IT and telecommunications equipment, *CE* consumer equipment, *LE* lighting equipment, *GDL* gas discharge lamps, *EET* electrical and electronic tools, *TLSE* toys, leisure and sports equipment, *MD* medical devices, *MCI* monitoring and control instruments, *AD* automatic dispensers

India

WEEE and WEEP recycling has been documented thoroughly in informative reports supported by EMPA [7] and Naturvårdsverket [50].

The USA

Probably, the USA is still the largest household WEEE producer. Yet, there is no federal mandate to recycle e-waste. Nevertheless, many states have instituted mandatory electronics recovery programs featuring distinct financing modes. Some American Corporations (HP) pioneered responsible methods of WEEE management, including take-back systems and design for recycling [37].

EPA encourages reuse and recycling of used electronics, including those that test hazardous, such as colour CRTs and cell phones. Computer monitors and televisions (TVs) sent for continued use (either resale or donation) is not considered hazardous waste, which would otherwise require special handling requirements. Unused circuit boards are considered unused commercial chemical products, which are unregulated. Used circuit boards meet the definition of spent materials and also that of scrap metal. Therefore, they are exempt from hazardous waste regulations. Shredded circuit boards cannot contain mercury switches or relays, nickel/cadmium or lithium batteries; otherwise they are considered hazardous waste [51].

Design for environment

Design for environment is a perspective optimising the environmental characteristics of a product, process or facility. Product stewards and designers identify and recommend environmental improvements with three priorities [52]:

1. Energy efficiency—reduce the energy needed to manufacture and use products.
2. Materials innovation—reduce the amount of materials in use; develop materials with less environmental impact and more value at end-of-life.
3. Design for recyclability—equipment easier to upgrade or recycle.

These priorities are achieved by:

- Placing environmental stewards in every design team to identify changes that may reduce environmental impact throughout the product's life cycle.
- Eliminating the use of legacy flame retardants where applicable.
- Reducing the number and types of materials used, including the plastic resins.
- Using moulded-in colours and finishes stead of paint, coatings or plating.
- Reducing energy consumption.
- Increasing use of recycled materials in product packaging.
- Minimising product or packaging materials.
- Designing for disassembly and recyclability by implementing the ISO 11469 plastics labelling standard, minimising the number of fasteners, and the tools necessary for disassembly.

Reducing the environmental impact of a product begins at the design and manufacture stage, where reducing the use of hazardous substances is most effective [53].

Hazardous aspects of WEEE

WEEE contains a host of different elements, many of which are environmentally or occupationally problematic, as well as persistent organic pollutants (POPs) or potential precursors of POPs [54].

WEEE recycling raises a number of occupational and environmental issues: phthalates, Pb, Cd, Hg in batteries and Ba, Pb, Hg and rare earth elements (REE) contained in CRTs could be leached from dumps; legacy BFRs and polychlorobiphenyls (PCBs) contained in capacitors could spread into the environment if ignited. If hazardous substances have been used, then the e-waste is best reused or recycled to reduce their environmental impact [54].

Table 8 Maximum concentrations in six single substances of WEEE, according to the RoHS directive

Element or compound	Maximum permitted level (wt%)
Lead (Pb)	0.1
Mercury (Hg)	0.1
Cadmium (Cd)	0.01
Hexavalent chromium (Cr^{VI})	0.1
Polybrominated biphenyls (PBB)	0.1
Polybrominated diphenyl ethers (PBDE)	0.1

The RoHS directive and its requirements

Only six substances are singled out for their hazardous character by the RoHS Directive [55], which deals mainly with the elimination and reduction aspects of the waste hierarchy, yet addresses only four steps of this ladder (Scheme I). Starting from 2006, manufacturers were required to demonstrate that their products do not contain more than the maximum permitted levels of the following elements or compounds (Table 8):

These limit values apply to any individual homogeneous material, i.e. to a single substance; e.g. the plastic used in the insulation of a wire. The assembly of (wire + insulation) is not a single substance, but a component. A component may contain several materials to be each considered separately. Later, RoHS was adapted by Directive 2011/65/EC. Specific substances can be restricted under RoHS, if they could:

- give rise to uncontrolled or diffuse release of the substances or hazardous residues during E&E waste collection or treatment processes,
- lead to unacceptable workers exposure in the E&E waste collection or treatment processes,
- be replaced by substitutes with less negative impacts.

The Basel convention

The Basel convention has identified e-waste as hazardous and developed a framework for controlling its transboundary movements. The Basel ban, an amendment to the Basel convention, aims at altogether prohibiting its export from North to South, yet it has not yet come into force [56].

Brominated fire retardants

Fire or flame retardants are materials or substances that provide increased resistance to ignition, slow down combustion and delay the spreading of flames. Fire retardants generally come in different formulations and application modes, e.g. as brominated, phosphorus and nitrogen compounds, intumescent coatings, mineral charges, metal hydroxides. The most powerful fire suppressants are the BFRs, often used together with synergetic antimony oxide (European Flame Retardants Association: www.flameretardants.eu). BFRs are applied to 2.5 M tonnes of polymers annually, with an annual consumption of PBDEs of >40,000 Mg. Some reactive BFR systems are extremely expensive.

The electronics industry accounts for the greatest consumption of BFRs, more than in cars or furniture. In computers, BFRs are used mainly in the pcbs, connectors, plastic covers, and cables. BFRs are also often used in plastic covers of television sets and domestic kitchen appliances.

BFRs are incorporated into plastics, either into the molecules, through reactive brominated monomers, or as additives, in particular in those plastic parts or castings used under extreme conditions, e.g. in cables, contactors & connectors, enclosures, and pcbs. Such extreme operating conditions were described vividly [57] as follows: Connectors involve a complex association of dielectric (engineering thermoplastic resins for low voltage alternative/direct current) and metal parts. High voltage is not necessary to develop fire due to electric malfunctioning, but a local increase in resistance can create a source of ignition. While the ignitable material is definitely plastic, the actual ignition cause can be linked to both metal and plastic parts. For metal parts, causes can include a copper/alloy oxidation that reinforces the resistance of the contact. That resistance can cause an arc creation during switching off, with risk of arc propagation, or an electric overload that melts the metal and the dielectric together and sticks the contactor. Regarding the plastic, causes are numerous. They can include the (in)ability to bear short overload without melting or degrading. Heat exposure over time can also modify the dielectric strength of the resin and create new bypath ways for current. Water diffusion via cables can create an electrolytic effect and develop wet tracking. Constant switch on/off can lead to soot deposits over time, cause of surface arc tracking. Progressive off-matching of male and female parts (vibration, dilatation, etc.) can finally create an increasing gap, enhancing resistance and heat dissipation.

Reducing flammability is imperative, given the extreme operating conditions of some e-components on the one hand, the hazard of having EEE taking fire in living or working surroundings on the other hand. Some 75 different BFRs are (or were) produced with widely varying physical and chemical properties, e.g.

- Polybrominated diphenyl ethers (PBDEs), mainly DecaBDE, a candidate for Authorisation under REACH, the EU‘s regulatory regime on chemicals.
- OctaBDE and PentaBDE, used since the 1950s, no longer manufactured since 2004.
- Polybrominated biphenyl (PBB), phased out since the late 1970s.
- Hexabromocyclododecane (HBCD or HBCDD).
- Tetrabromobisphenol A (TBBPA or TBBP-A) used in pcbs, as a reactive and also as an additive BFR applied in acrylonitrile butadiene styrene (ABS). Since it is chemically bound to the resin, it is less easily released into the environment.
- Brominated polystyrene, as a brominated monomer.

Technical specifications for each major application are covered by the website of the European Flame Retardants Association [58]. The datasheets of the BFRs still authorised under RoHS figure on this website. Depending on their age, WEEP may also contain Legacy Additives prohibited under RoHS, e.g. PBBs, OctaBDE and PentaBDE. Their presence in WEEP was investigated leading, e.g. EMPA to the following general conclusions [10]:

- Decabromodiphenyl ether (DecaBDE): the maximum concentration value (MCV) is expected to be exceeded in HIPS (monitor housings, television sets, video devices).
- Octabromodiphenyl ether (OctaBDE): the MCV is expected to be exceeded in ABS (monitor housings, television sets, video devices).
- Pentabromodiphenyl ether (PentaBDE): except for PUR, the MCV is probably not exceeded.
- PBBs: concentrations well below the MCV are expected in all plastic types.

The amounts of BFR typically applied are shown in Table 9 [59]. The potential presence of Legacy Additives jeopardises mechanical recycling, not only of those WEEP certainly comprising Legacy BFRs, but also of much wider mixes that could comprise minor amounts of these as contaminants, e.g. in mixed plastics proposed for physical separation. Systems have been developed to try and sort out these BFRs-containing materials (on the basis of their higher density, by spectroscopic methods) or to extract their BFRs using solvents (Creasolv®) [60].

Thermal solutions, i.e. controlled incineration, gasification, or pyrolysis, including the recovery and recycling of Br and Cl flows, have been established and tested, often in collaboration with FZ-Karlsruhe and ECN [61–63]. Grabda et al. [64] used nascent bromine to recover metals from WEEE.

WEEE management

Survey

Global e-waste management comprises numerous and complex issues [56]. Currently, the main technical options

Table 9 Amounts of BFR typically incorporated [59]

Polymer	Content (wt%)	Substances
Polystyrene foam	0.8–4	HBCD
High-impact polystyrene	11–15	DecaBDE, brominated polystyrene
Epoxy resin	0–0.1	TBBPA
Polyamides	13–16	DecaBDE, brominated polystyrene
Polyolefins	5–8	DecaBDE, propylene dibromostyrene
Polyurethanes	n/a	No brominated FR available
Polyterephthalate	8–11	Brominated polystyrene
Unsaturated polyesters	13–28	TBBPA
Polycarbonate	4–6	Brominated polystyrene
Styrene copolymers	12–15	Brominated polystyrene

for e-waste elimination are reuse, remanufacturing, and recycling, as well as incineration and landfill. The e-waste recycling chain comprises three main steps: collection, sorting/dismantling, and processing.

Reuse

Electronic equipment discarded by the original purchaser still has value for other users, therefore it can be resold or donated to schools or charities (EPA—eCycling frequent questions). Reuse extends the usable lifespan of equipment and reduces the volume of waste to be treated. Remanufacturing involves disassembling, cleaning, repairing or refurbishing, reassembling and testing to produce like-new equipment [65]. Recycling e-waste materials for their original or other purposes, involves disassembly, removal of hazardous components and destruction of the end-of-life equipment to recover materials, generally by shredding, sorting and grading.

Managing WEEE can be directed by economic considerations (precious metals in pcbs) and/or by the desire to manage hazardous materials responsibly. The WEEE Directive created a third drive: attaining elevated and possibly even unworkable recycling rates. WEEP plastics arise as a mosaic of different types of resins and additives, dispersed in multitudes of small amounts and hypothecated by the presence of BFRs, as well as heavy metals and dirt. Some pollutants (additives) are intrinsic; others became embedded during shredding and other operations to recover precious or ordinary metals.

Mechanical recycling of plastics refers to processes, which involve reprocessing plastics by shredding, melting, or regranulating.

Feedstock recycling or *chemical recycling* refers to techniques used to break down plastic polymers into their constituent monomers, which can be used again in refineries, or petrochemical production. In practice, the product distribution is so complex that only rarely commercial operation is sensible, namely when high-value monomers are obtained with a good yield. Excellent research was devoted to the elimination of halogens prior to, during, or after pyrolysis [66, 67]. The fate of brominated flame retardants was studied by Grause et al. [97] during the pyrolysis of high-impact polystyrene containing brominated flame retardants.

Thermal recycling refers to incineration with heat utilisation and/or power production. Combined heat and power generation allows attaining much higher efficiencies.

Collection and transportation

Around 20–50 M tonnes of WEEE are generated worldwide every year [68]. In 2004, ca. 1.82 Mt of plastic destined to EEE was produced in EU-27 (2003: 1.78 Mt). In 2008, 1.4 Mt of plastic waste was generated from EEE [69]. Electrical and electronic devices have an average service life of 3–12 years, with large objects having longer service life. The quantities of WEEE collected from households vary considerably, yet the overall time trend is rising. It may take some time before recyclable plastics begin to be collected in higher amounts. Prof. Salhofer [70] compared collection methods applied in Austria and in Europe and also shows composition data where a hazardous fraction is singled out.

Physical amounts and numbers

The flow of e-waste is unusually diverse, both in its dimensions and composition, ranging from handheld tools to a large refrigerator. After lifetimes that may vary from months to (theoretically) generations, such EEE spontaneously converts into e-waste. Eurostat presents statistical material from the member states for the time period 2005–2010 (items enumerated in Tables 10, 11). Historical data are described in Tables 10 and 11 (start of the century), collection intensity is shown in Fig. 5 [36]. In weight units, the largest flows are the large household appliances, closely followed by IT equipment and by audio and video equipment. Lamps arrive in largest number, followed by IT equipment, small and large household appliances, and audio and video equipment (Table 12) [71]:

The largest PoM flow, on a per capita basis, stems from Norway (with >40 kg/cap., year), followed at some distance by other affluent countries in Northern and Western Europe (20–30 kg/cap., year); the poorer Member States remain at a level of 10–15 kg/cap., year. Norway's EEE

Table 10 Amounts of (1) products put on the market; (2) waste collected; (3) waste collected from households; (4) waste collected from other sources; (5) treated in the member state; (6) treated in another member state of the EU; (7) treated outside the EU; (8) reuse; (9) recovery; (10) total recycling and reuse [36]

Year 2010	Products put on the market	Waste collected	Waste collected from households	Waste collected from other sources	Treated in the member state	Treated in another member state of the EU	Treated outside the EU	Reuse	Recovery	Total recycling and reuse
Total, in metric tonnes	9574735	3299163	3106472	192691	2775052	143284	16565	69369	2259808	2062092
Large household appliances	48.9	47.2	48.4	26.9	47.3	42.8	20.3	38.5	45.4	46.2
Small household appliances	9.0	6.2	6.4	3.8	6.8	5.1	6.0	4.6	7.0	6.6
IT and telecommunications equipment	15.5	21.7	20.8	35.1	21.5	22.1	21.9	46.5	19.8	19.5
Consumer equipment	10.2	19.4	20.3	5.5	18.7	23.0	32.4	6.7	21.8	21.7
Lighting equipment	4.4	0.8	0.5	6.0	0.7	1.4	5.8	0.3	0.9	0.9
Gas discharge lamps	1.2	1.1	0.8	5.3	1.1	2.5	0.6	0.3	1.2	1.4
Electrical and electronic tools	5.3	2.3	2.1	4.5	2.4	1.9	9.0	0.9	2.4	2.3
Toys, leisure and sports equipment	2.6	0.4	0.4	1.5	0.4	0.4	0.3	0.9	0.5	0.5
Medical devices	0.9	0.3	0.1	3.5	0.3	0.2	0.4	0.4	0.3	0.3
Monitoring and control instruments	1.3	0.3	0.2	2.0	0.3	0.4	3.0	0.1	0.3	0.3
Automatic dispensers	0.6	0.4	0.0	6.0	0.4	0.3	0.1	0.8	0.5	0.4
Sum (wt%)	100	100	100	100	100	100	100	100	100	100

data seem somewhat inflated by a wider coverage than in other countries [72].

Recycling of WEEE and of WEEP

Reuse: remanufacturing

Most obsolete EEE can still be sold or donated to less demanding users, if required, after repair or revamping. These activities are accomplished by charitable, not-for-profit organisations. As an alternative, spare parts are reclaimed, for incorporation in equipment requiring repairs. *Remanufacturing* has evolved into an important activity. Some parts in widespread use are supplied at a cost far below that of the original equipment manufacturer, e.g. toner cartridges.

Disassembly

Manual dismantling is essential for removing hazardous components and the best, yet most expensive way to prepare for recycling. Procedures vary from one EEE to another. Unfortunately, the quality of decontamination is also variable. In Austria, the mass of selected components removed and the corresponding mass of hazardous substances were compared to input value estimates. Decontamination was still incomplete, ranging from 72 % for batteries to 21 % for liquid crystal panels. This implies the forwarding of hazardous substances to mechanical treatment plant. Easily releasable pollutants, such as Hg from LCD backlights, Cd from batteries or highly contaminated dust, pose substantial health risks for plant workers. Low removal rates reduce the recovery of valuable recyclable materials [8].

Disassembly studies strive to develop procedures, software and tools for formulating disassembly strategies and configuring disassembly systems [53, 73–78]:

- Input and output product analysis: all major reusable, valuable, and hazardous components and materials are defined. After cost analysis, optimal disassembly procedures are identified.
- Assembly analysis: joining elements, component hierarchy and former assembly sequences are analysed.
- Uncertainty issues: identifying potential defective parts or joints in the incoming product, upgrading/downgrading during consumer use, and disassembly damage.
- Dismantling strategy: using non-destructive or destructive disassembly.

Table 11 Idem, relative amounts of (1) products put on the market = 100; (2) waste collected; (3) waste collected from households; (4) waste collected from other sources; (5) treated in the member state; (6) treated in another member state of the EU; (7) treated outside the EU; (8) reuse; (9) recovery; (10) total recycling and reuse

Year 2010	Products put on the market	Waste collected	Waste collected from households	Waste collected from other sources	Treated in the member state	Treated in another member state of the EU	Treated outside the EU	Reuse	Recovery	Total recycling and reuse
Total	100	34	32	2	29	1	0	1	24	22
Large household appliances	100	33.2	32.1	1.1	28.0	1.3	0.1	0.6	21.9	20.3
Small household appliances	100	24.0	23.2	0.9	22.0	0.9	0.1	0.4	18.4	15.8
IT and telecommunications equipment	100	48.0	43.5	4.5	40.1	2.1	0.2	2.2	30.0	27.1
Consumer equipment	100	65.7	64.6	1.1	53.3	3.4	0.6	0.5	50.4	45.8
Lighting equipment	100	6.1	3.4	2.8	4.9	0.5	0.2	0.0	4.7	4.2
Gas discharge lamps	100	29.8	21.2	8.6	26.3	3.1	0.1	0.2	23.6	23.6
Electrical and electronic tools	100	14.7	13.0	1.7	13.2	0.5	0.3	0.1	10.6	9.5
Toys, leisure and sports equipment	100	5.7	4.5	1.1	5.0	0.2	0.0	0.2	4.3	3.8
Medical devices	100	10.2	2.7	7.5	8.6	0.3	0.1	0.3	7.3	6.7
Monitoring and control instruments	100	8.1	4.9	3.2	6.4	0.4	0.4	0.0	5.8	5.4
Automatic dispensers	100	20.7	1.6	19.1	18.8	0.7	0.0	1.0	17.6	14.6

Research on disassembly has been an active area with hundreds of papers written on this subject. Characterisation of WEEE is essential prior to the development and testing of treatment and separation schemes. Depending on its sources and treatment, e-waste shows different characteristics and composition. In principle, most large plastic parts can now be singled out.

Particle classification methods

The recovery of metals passes by particle classification methods, applied after removing hazardous parts and shredding, to liberate embedded or composite metal parts. Larger parts are retrieved first by magnetic and then by eddy current separation, retrieving ferrous and nonferrous metals, respectively. Metals are denser than plastics and separated using usual ore dressing equipment, such as jigs, shaking tables, corona electrostatic separation, etc. [79].

Sizing is not only used to prepare a more uniform feed for further processing, but also to classify fractions showing distinct composition: some materials report to the larger or the finer fractions, because of their original dimension, toughness or brittleness. Sizing most commonly uses either rotary cylindrical trommels or vibratory screens. Blinding is a major problem [80].

Shape separation techniques have been developed mainly for the powder industry. They make use of differences in particle velocity on a tilted solid wall, the time particles take to pass through a aperture, cohesive force of the particles to a solid wall, and settling velocity in a liquid [81–84].

Density separation is a major step in classifying plastics by resin types. Polyolefins float in water, styrenics in brine of sufficient density. The dense fraction contains metal composites (wire), PVC, and PET. Wood-derived materials are light when dry; once wet they jeopardise separation [85] (Fig. 6).

Surveys of separation techniques are presented by Forssberg et al. [32, 79, 86]. Thorough metal separation and further particle classification are required to separate mixes of WEEP into individual resin classes. If they can be processed up to an acceptable level of purity, then they can be regranulated and proposed commercially as a recyclate.

Mechanical recycling

According to Plastics Europe, mechanically recycled plastics coming from EEE represent <2 % of the total amount of mechanical recycling of plastics [87]: the origin of this material is mainly large domestic appliances (e.g.

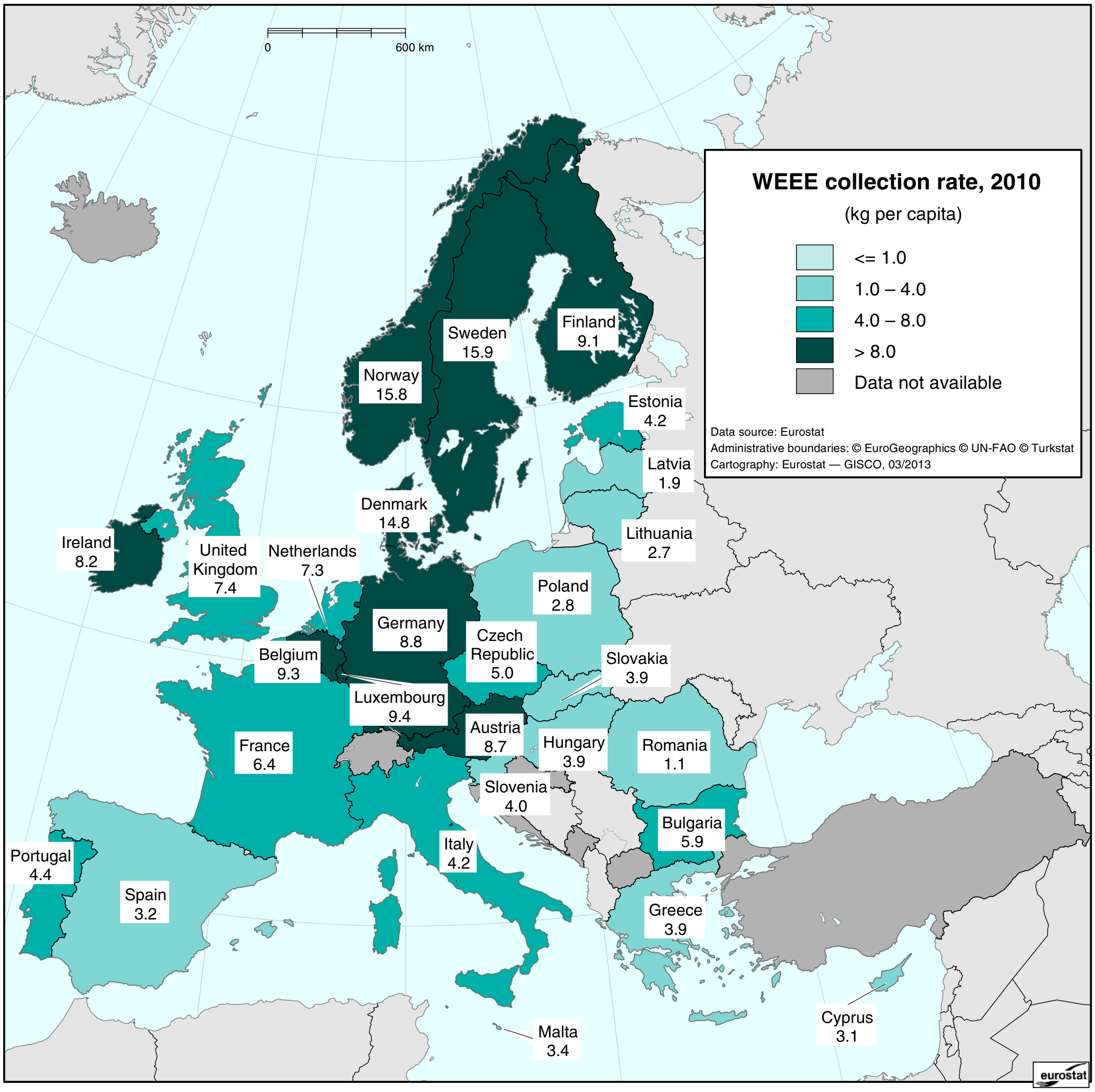

Fig. 5 Map of Europe with collection intensity [36]

refrigerators). The inner liner of refrigerators is an example of an appliance with an increasing recycling rate.

Mechanical recycling refers to the reprocessing of WEEP to form new plastic products with similar (or lower) performance than the original products. WEEP is thoroughly liberated from non-plastics and then sorted per resin before further processing. A balance is struck between purity and yield of recovery of the sorted fractions. Ideally, batches of one resin and set of additives are singled out at the source: specific equipment is likely to be dismantled on one line and presumably the recovered plastics satisfy similar specifications. Yet, even equipment casings show limited recycling opportunities because of the large number of resin types used; moreover, plastic parts are not often labelled according to their type of resin.

Most resins and some additives are mutually incompatible. Figure 7 shows the internal compatibility of plastic resins with and without BFRs. A wide variety of brominated flame retardants have been used in some plastic components. Not only the particular resin and additives, but also the types of flame retardants present needs to be taken into account. The presence of chlorinated and brominated compounds may require measures for protecting human health in operations where these plastics are shredded, converted or heated [53] (Fig. 7).

Logically, mechanical recycling will be limited to plastics selected at reliable sources.

A second issue is to find suitable outlets. Determining which markets may use the plastics found in consumer electronics, the value of the plastics in those markets, and the

Table 12 Amount of e-waste in each of the 10 categories [66]

Equipment	Units (millions)	Weight (k tonnes)	% 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

level and complexity of separation necessary to get these into usable forms all relate to viable recycling. If recycled plastics are to be used in high-end products, the physical and mechanical properties of recovered resins must meet those of virgin resins. In addition, a major concern in plastics recycling is the need to separate the plastic types and identify additives and contaminants. It may be necessary to reduce the number of resins used in electronics to make their recycling feasible, just like in automotive industry [88, 89].

Several equipment manufacturers propose equipment suitable to separate plastics in resins of different density or electrostatic charging. Other separating methods, such as froth flotation work perfectly when separating virgin resins, yet they still remain largely unused, because the polymer surface is modified either on purpose (electrostatics, embellishing), or during use (surface ageing and oxidation). Potential suppliers are Galloo, hamos, Sicon… Bühler provides optical sorting solutions for a variety of plastics (PET and HDPE flakes, uPVC off-cuts, WEEP, PVB, PP, ABS, PS), as well as colour grouping and wire recovery to maximise product value.

Waste and Resources Action Programme (WRAP, the U.K.) commissioned studies on the separation of WEEP (Table 13) and the cost and environmental benefits of using recyclate [90]. Both Indesit and Electrolux have used WEEP in commercial products.

MBA polymers [91], Galloo and Sims all recycle plastics from WEEE at an industrial scale. Recently, recycling of flat panel displays (FPD) incorporating BFRs has been demonstrated [92].

In view of the challenge to comply with legislation, it is prudent to explore the benefits of other end-of-life options such as chemical feedstock recycling and energy recovery as alternative to mechanically remove heavy metals and halogens from EEE plastics. Regarding legacy additives an older APME report, as well as recent EMPA reports provide answers to two key questions [85, 93]:

- What are the concentrations of RoHS-regulated substances in mixed plastics from selected WEEE categories and products?
- What are the implications for an environmentally sound recovery of plastics from WEEE?

Additionally, attention was paid to the possible formation of toxic PBDD/Fs when WEEP was exposed to thermal stress [94, 95]. Demonstration projects were launched to prove the feasibility of mechanically recycling resins incorporating BFRs, e.g. FPD [90].

Creasolv®

Plastic resins may be separated using suitable solvents, to extract the soluble resins among them from mixtures. Also additives such as plasticisers may be extracted [96, 97].

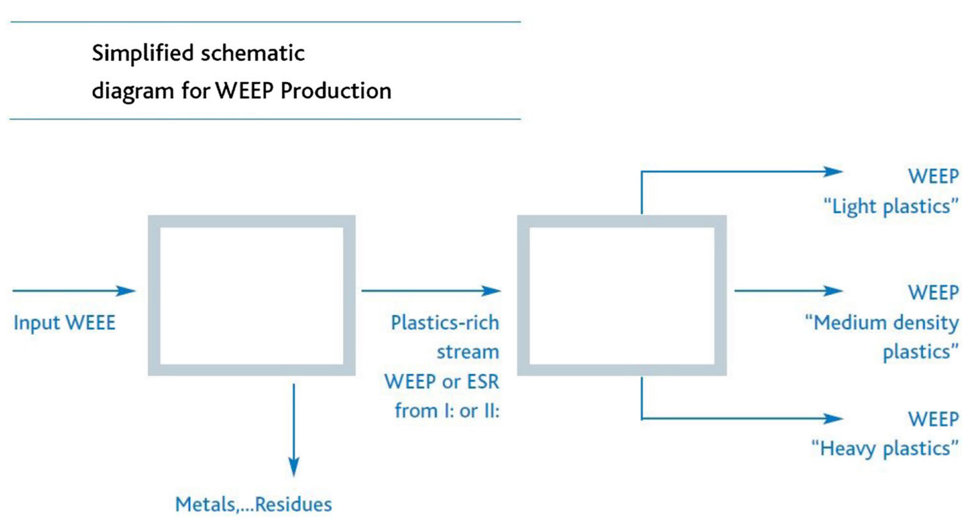

Fig. 6 APME diagram for WEEP production [85]

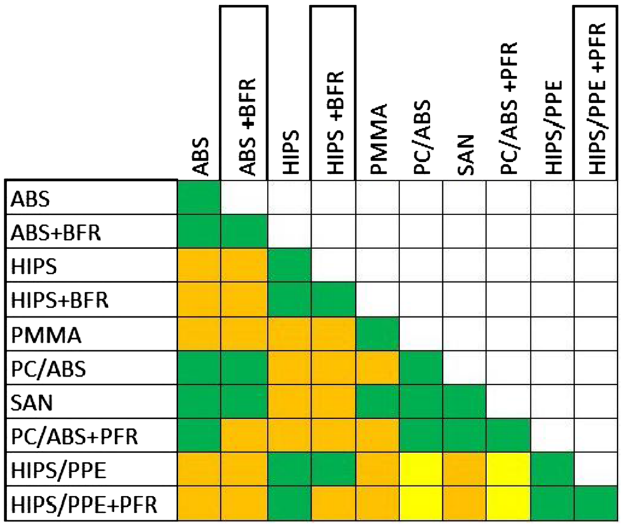

Fig. 7 Internal compatibility of plastic resins with and without BFRs [92]

Table 13 Technical equipment tested by axion in WRAP-commissioned studies [adapted from 80]

Separation technique	Equipment tested
Shape, size and density separators	Allmineral Alljig (wet jig)
	Delft University of Technology kinetic gravity separator (KGS)
	Holman Wilfley wet shaking table
	Allmineral 'Allflux' up flow classifier, and University of Nottingham pneumatic dry jig
	Alvan Blanch 'Destoner' air table
Milling	Pallmann PXL18 differential impact mill

The Fraunhofer Institute for Process Engineering and Packaging IVV (Freising, Germany) developed the patented CreaSolv® method, a selective solvent extraction process for recycling WEEP that is separated and recovered in high purity. Particular contaminants are removed with retention of all polymer properties of the base resin. The three main steps are:

- Dissolving the target plastic with a selective solvent.
- Separating non-dissolved substances from the polymer solution.
- Precipitating the target plastic from the purified polymer solution.

This recycling process is currently proposed for the flame-retarded ABS arising from WEEP and automotive shredder residue (ASR); it was tested and optimised at laboratory scale and positively evaluated in collaborative projects with WRAP, Sicon, etc. The above process can be completed with preliminary sorting and shredding and then is followed by concentration, drying, compounding. Analytical characterisation of input/output is essential. Other applications include densification of voluminous EPS and pigment separation from ABS [62]. Solvay operates a similar process in Ferrara, Vinyloop®, to separate PVC from composites [98]. Also, supercritical carbon dioxide allows extracting high-priced BFRs [99, 100].

Feedstock recycling

Feedstock recycling converts WEEP into fuels, monomers or other chemicals by thermal decomposition (pyrolysis) or into synthesis or fuel gas by gasification. Pyrolysis consumes only 10 % of the energy content of WEEP [94, 101], yet may form PXDD/Fs [102–105]. Pyrolysis products from mixed non-descript feedstock are unlikely to be saleable. Product distributions should be established experimentally and are influenced by a host of factors, such as impurities. Antimony trioxide increased oil formation in Br-HIPS pyrolysis, yet diminished the oil/wax yield from a Br-HIPS + polyolefin mixture [106].

Also dehalogenation is required, because straight pyrolysis oils contain halogenated organics. Dehalogenation and decomposition can be carried out successively, i.e. prior to or after pyrolysis, or simultaneously. A first strategy is two-stage pyrolysis releasing halogen hydrides (HCl, HBr; temperatures <350 °C), followed by thermal decomposition of residual polymer matrixes (ca. 450 °C), producing (almost) halogenated-free oil products. A second strategy removes organic halogen during cracking using zeolites or other catalysts. Dehalogenating pyrolysis products is the third strategy.

Dehalogenation of aromatic halides proceeds on metals (Fe, Ni, Zn, etc.) [107–112]. Metallic calcium in ethanol was highly effective already at ambient temperature [107, 108]. Possible Ullmann reactions (i.e. coupling of aryl halides with copper) have been extensively studied [109–112]. A zinc dust/sodium hydroxide/ammonium formate system is effective for debrominating TBBPA to Bisphenol A [106].

Pyrolysis faces a combination of negative technical and economic factors, such as the small scale (ca. 10 % of packaging plastics) of operations, the complexity of the feed (>20 different plastic resins, part of which thermosets), and the presence of fire retardants and catalytic metals.

Energy recycling

Energy recycling liberates the chemical energy in WEEP as heat and power.

A major issue is the presence of BFR, with possible quenching of flames, less complete combustion and subsequent formation of PXDD/Fs (X = Br or Cl). Thermolysis of certain brominated flame retardants results in the formation of PBDD/Fs [113–116]. The pyrolysis of PBB results in the formation of PBDFs in concentrations of up to ca. 2 mg g^{-1}. High PBDD/Fs concentrations were found to result from the combustion of television sets [117] and electrical appliances or their casing parts in experimental fire tests simulating real fire conditions [118]. The total PBDD/F concentrations in combustion residues reached values between 1 and 9000 µg g^{-1}. Their concentration in the smoke samples ranged between 0.8 and 1700 µg m^{-3} [117, 118], Weber et al. [119] found that bromine and chlorine resemble in their formation of PXDD/Fs from their respective precursors, as well as during *de novo* synthesis. Nevertheless, BFRs can be destroyed with high efficiency under controlled combustion conditions and then may not serve as precursors for PXDD/Fs formation. High temperature (>850 °C) and long residence times (>2 s) are required to ensure complete destruction [120].

Also heavy metals may be problematic. Typical WEEP analyses show 5.6 % of ash, 2.07 % of Cl, 1.46 % of Br and 0.49 % of Sb. The elements As, Cd, Co, Cr, Cu, Hg Mn, Ni, Pb, Sn, Zn were evident in a range from 1 to 1000 ppm. Tl or V was undetectable [85].

Since the early 1990s, the global plastics industry has launched a large number of R&D and demonstration projects to test integrated resource management options for various plastics. PlasticsEurope (previously *Association of Plastics Manufacturers in Europe*, or APME), the Plastics Waste Management Institute of Japan (PWMI) and the American Plastics Council (APC) have led such efforts. Mechanical recycling, feedstock chemical recycling, fuel recovery, and energy recovery technologies all advanced significantly through this work [121]. Cfr. Figure 1 in [89].

Conclusions

EEE is diverse and complex with respect to the materials and components used and waste streams from the manufacturing processes. Characterisation of these wastes is of paramount importance for developing a cost-effective and environmentally sound recycling system. The development of a stable recycling industry will depend 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, recycling depends on manual operations. In addition, current 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 waste.

Treatment and recycling of e-waste is an emerging waste management problem, as well as a business opportunity of increasing significance, given the rapidly rising volumes of e-waste being generated and their content of both valuable and toxic materials. WEEE or e-waste has been taken into consideration not only by government, but also by the public due to their contents of rare and hazardous materials [122–125]. Since EEE is an important potential source of waste plastic, Directive 2002/96/EC on WEEE has some important implications for plastics recycling. The Directive sets out design requirements, resulting in a gradual reduction in the variety of plastics used in EEE products. The Directive emphasises recyclability of product components, though their technical and economic feasibility remain precarious.

Recycling plastics from s-WEEE is still unusual: it is strongly subordinated to recovery of the (precious) metals present and the value of eventually recoverable plastics should be weighed against the environmental risks related to its hazardous features. These derive mainly in the presence of BFR and heavy metals.

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