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Assessment of removal of components containing hazardous substances from small WEEE in Austria

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ABSTRACT

Minimum treatment requirements for waste electrical and electronic equipment (WEEE) established by Directive 2002/96/EC provide for the removal of specific components containing hazardous substances. To date, no comparative analysis of removal rates has been undertaken. The present paper examines the state of de-pollution of sWEEE in Austrian treatment plants. The mass of selected components removed and the corresponding mass of hazardous substances is compared to estimated values for sWEEE input material. The results obtained reveal that components are only partly removed, featuring a high variation between components and plants assessed. The overall rate of removal ranged from 72% of the estimated value for batteries to 21% of the estimated value for liquid crystal panels. This implies the forwarding of substantial quantities of hazardous substances to mechanical treatment processes, particularly relevant in terms of dispersion of pollutants. Furthermore, easily releasable pollutants, such as Hg from LCD-backlights, Cd from batteries or highly contaminated dust in general, pose substantial health risks for plant workers. Low removal rates of printed circuit boards, batteries and toner cartridges also lead to a reduction in quantities of valuable recyclable materials (precious metals, plastics).

1. Introduction

Minimum treatment and technical requirements to be applied in the storage, treatment and recovery of waste electrical and electronic equipment (WEEE), including targets for recycling and recovery to be achieved with regard to individual WEEE categories, are laid down by the Directive 2002/96/EC (WEEE Directive, last amended by 2008/34/EC) with specific provisions covering the selective treatment of materials and components. Annex II (1) to the Directive specifies a total of 15 substances, preparations and components to be mandatorily removed from separately collected WEEE ("de-pollution").

The following components are present in small waste electrical and electronic equipment (sWEEE): capacitors (all capacitors containing polychlorinated biphenyls and electrolyte capacitors larger than 25 mm), batteries, printed circuit boards (of mobile phones generally or larger than 10 cm^2), toner cartridges, liquid crystal displays (larger than 100 cm^2 and those back-lighted with gas discharge lamps), mercury-containing components such as switches and backlighting lamps, asbestos-containing components, components containing refractory ceramic fibres, components containing radioactive substances, plastic-containing brominated flame retardants and external electric cables. A second group comprising cathode ray tubes and halogenated coolants are not classified as sWEEE components.

The WEEE Directive establishes no provisions however as to how the level of de-pollution achieved should be demonstrated, nor a description of the best available technology to be applied in removal of components containing hazardous substances. In Austria and other European countries two main technologies are applied in the treatment (including removal of components containing hazardous substances) of sWEEE. The first is manual dismantling whereby appliances are opened and components (both hazardous and valuable) are removed. The second technology initially applies mechanical processes to break up appliances, in a second step providing for the manual sorting of hazardous (and valuable) components along conveyor belts.

The rate of de-pollution of sWEEE achieved by currently applied treatment technologies has not been assessed to date. Furthermore, no estimation of the percentage of components containing hazardous substances derived from separately collected sWEEE actually forwarded to treatment facilities is currently available. The present paper examines the removal of selected components from separately collected sWEEE during treatment processes. The amount of hazardous substances removed or forwarded to additional treatment processes is evaluated. It should however be taken into account that a substantial part of sWEEE is not collected separately but is disposed of as residual waste or metal scrap.

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Table 1
Composition of small WEEE, share of sub-categories and examples for typical appliances in the overall WEEE stream in Europe.

No.	Subcategory	Typical appliance	Share (mass%)
1C	Large household appliance – small	Microwave, electric heating appliance	3.63
2	Small household appliance	Vacuum cleaner, toaster, iron, kettle, electric fan, electric toothbrush	7.01
3A	ICT (excl. CRTs)	PC, keyboard, printer, telephone, laptop	8.00
4A	Consumer electronics (excl. CRT)	Video recorder, hifi, speaker, radio, remote control, SAT receiver, DVD/CD player	7.82
5A	Lighting equipment	Luminaire	0.70
6	Electrical and electronic tools	Lawn mower, strimmer, pump, garden shear	3.52
7	Toys	Game console	0.11
8	Medical devices	Blood pressure meter	0.12
9	Monitoring and control units	Smoke detector	0.21
	Total		31.12

ICT, information and communication technology; CRT, cathode ray tube; rem.: 100% = total WEEE stream in Europe.

2. Methodology

At the start of the study, the mass of selected components containing hazardous substances in sWEEE was estimated (see Section 3.1). On the basis of the hazardous substance contents of these components, a hazardous substance inventory for mixed sWEEE was drawn up (see Section 3.2). Data concerning the removal of components containing hazardous substances in Austrian treatment plants were obtained from a survey undertaken in 2007/8 (see Section 3.3). Removal rates were then compared with estimated quantities in the sWEEE-mixture treated by the respective treatment plant (see Section 3.2). De-pollution was finally assessed on the basis of removal rates of hazardous substances, taking into account potential environmental impacts (i.e. dispersion of pollutants by introduction of components into downstream waste treatment processes such as shredders, incineration or material recovery processes), health risks for plant staff and impacts on the recycling of valuable materials.

3. Composition of sWEEE

3.1. Mass of selected components containing hazardous substances

To characterise input into sWEEE treatment plants, both the share and the composition of individual types of appliances was considered. In addition to the categories specified in Annex IB of the WEEE Directive, sWEEE comprises several subcategories. Table 1 illustrates subcategories, typical types of appliances and mass share of the overall WEEE stream in Europe [1].

Data on composition according to type of sWEEE appliances separately collected in Austria was obtained from the literature [2] and in the course of sorting analyses. Sorting analyses were conducted in 2006 and 2008 at larger treatment facilities for small WEEE in Austria. In 2006 a total sample of 28.2 t of sWEEE was sorted, and in 2008 24.0 t was sorted for a total of 7900 appliances.

With regard to the material composition of sWEEE, data present in the literature are rather lacking. DEFRA [3] has published results on an aggregated level (i.e. by sub-categories of appliances). Chancerel and Rotter [4] report data on composition according to types of appliances, although the material fractions only partly represent components containing hazardous substances. Therefore, to obtain information on composition according to type of sWEEE, dismantling trials were undertaken.

To clarify the composition of appliances the following components were defined: assemblies, sub-assemblies, material groups and materials. As an example, a PC comprises assemblies including housing, electronic parts, mechanics and cables. Sub-assemblies of electronics in a PC are represented by the CD drive, floppy drive, power supply, hard disk and printed circuit boards. Material groups include iron and steel, components containing hazardous substances, plastic, etc. Materials and material groups are shown in Table 2. While materials such as steel and aluminium can be identified by visual inspection, plastics should be analysed in an additional step.

In view of their high degree of significance in sWEEE the following components containing hazardous substances listed in Annex II to the WEEE-Directive were taken into consideration: capacitors, batteries, toner and ink cartridges, liquid crystal displays and printed circuit boards. Other components containing hazardous substances (mercury containing components, asbestos, components containing refractory ceramic fibres, components containing radioactive substances) were not taken into account, being used only in highly specific appliances. Moreover, plastics containing brominated flame retardants and external electric cables were not analysed in detail in this study.

The groups of materials reported in Table 2 were identified. “Iron and steel”, “Aluminium” and “Copper” were all recovered during the dismantling process, yielding a low quantity of unwanted materials, while “Cables” were compounds made of copper or aluminium and plastic. The “Plastic” group comprised all types of polymers. The material group “Mixed and other metals” included prevalently metal–plastic compounds, including motors or switches, and metals such as brass and magnesium. In Subcategories 2 and 6 this fraction accounted for a comparatively high share due to the presence of motors from vacuum cleaners and lawn mowers. Other materials included glass, wood, paper and ceramics.

The dismantling process was undertaken to achieve the separation of components containing hazardous substances. Secondly, assemblies and sub-assemblies were separated manually to obtain basic materials. Metal–plastic compounds such as motors could not be dismantled without specific equipment, and were therefore recorded as “mixed and other metals”. All dismantled parts were weighed and recorded, and separated according to type of assembly (housing, electronics, mechanics and wires). With regard to types of appliances no data pertaining to variation in composition were available; the sample was therefore selected according to weight share. In addition to the relevance of weight of appliances, focus was placed on appliances with a higher content of hazardous components, such as electric toothbrushes, laptops and remote controls. In practical trials, a sample of 227 appliances (842 kg) as illustrated in Table 1 was dismantled. The sample material was taken from municipal WEEE in the City of Vienna. The appliances analysed represent end-of-life equipment with a typical age of 7–10 years (see Chancerel, [5]). It is assumed that the sample material does not meet the requirements of RoHS, which was set in force by 2005.

Composition data were evaluated according to type of appliance. Using data from the sorting analysis, an average mix of appliances was calculated for each sub-category. To validate results, a dis-

Table 2
Material groups and materials.

Material group	Materials	Remarks
Hazardous	Capacitors, batteries, toner and ink cartridges, liquid crystal displays, printed circuit boards	All hazardous components in Annex II of the WEEE directive + LCD displays
Iron and steel	Iron, steel (sheet, cast, alloy)	Low share of unwanted materials (<5%)
Aluminium	Aluminium (sheet, cast, alloy)	Low share of unwanted materials (<5%)
Copper	Copper	Low share of unwanted materials (<5%)
Cables	External electric cables	Compound
Plastic	ABS (incl. blends like PC/ABS), PP, POM, PVC, PPO, undefined plastics	By plastic types, presence of flame retardants; not identified plastics are "undefined plastics"
Mixed and other metals	Metal–plastic compounds (switches, motors); other metals than iron, steel, aluminium, copper	Compounds like motors, etc., where manual dismantling is not possible
Others	Glass, rubber, ceramics, paper, wood	Residual materials from dismantling (small share)

Table 3
Comparison of components containing hazardous substances (kg/t) in dismantling trials and the dismantling campaign for selected types of appliances and subcategories.

	Dismantling trials	Dismantling campaign
Printer	75	76
Vacuum cleaner	6	8
Microwave	17	17
PC	99	127
HH small	8	9
CE	91	84

PC, personal computers; HH small, household appliances small (Sub-cat. 2), mix of 5 types of appliances; CE, consumer electronics (Sub-cat. 4A), mix of 6 types of appliances. Remark: Table does not give the same results for HH small and CE, as the mixture of types of appliances is different.

mantling campaign was undertaken at an Austrian dismantling facility. Sorted appliances (printers, microwaves, vacuum cleaners and personal computers) and mixed input (small household appliances and consumer electronics) were dismantled thoroughly, comparing the results with a calculated composition for the specific input. Components containing hazardous substances featured a deviation between measured and estimated share in the range of 1–23% (average 9%). Details for selected types of appliances and subcategories are shown in Table 3.

3.2. Hazardous substance inventory

The hazardous substance content for individual components and subtypes was obtained from the literature, as documented in Table 4. Hazardous substances considered comprised several (heavy) metals, brominated flame retardants, phthalates, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), "benzene, toluene, ethylbenzene, xylene" (BTEX), liquid crystals, toner dust as well as electrolytes from accumulators. Hazardous substance inventories of sWEEE mixtures were established by multiplying the hazardous substance contents of individual components by the mass of the respective components or subtypes of components (see Section 3.2) in the sWEEE mixture.

3.3. Removal at treatment facilities

In the course of a survey carried out from 2007 to 2008 at WEEE treatment plants in Austria [28], records were obtained from twenty sWEEE treatment plants with regard to quantities of sWEEE

Table 4
Literature references for average hazardous substance contents of components and sub-types applied in calculation of the hazardous substance inventory.

Component containing hazardous substances	Reference for average hazardous substance content of the component
Capacitors	
Capacitors >2,5 cm originating from Cat. 2	SENS, SWICO & SLRS [6]
Capacitors >2,5 cm originating from Subcat. 3 + 4A	
Capacitors >2,5 cm originating from Subcat. 1C	
Batteries	
Ni/Cd-batteries	Bräutigam [7], ERM [8], EPBA [9]
Button cells[a]	Bräutigam [7], Janz et al. [10], ERM [8], EPBA [9]
Ni-MH-accumulators	Bräutigam [7], Janz et al. [10], ERM [8], EPBA [9]
Li-ion-accumulators	Bräutigam [7], Janz et al. [10], ERM [8], Bipro [11]
Primary batteries (pred. AlMn and ZnC)[b,c]	Bräutigam [7], Janz et al. [10], ERM [8], BAM [12]
Toner and ink cartridges	
Toner catridges[d]	Hahn et al. [13], Jungnickel et al. [14], LGA [15]
Ink cartridges[d]	Not considered
Liquid crystal displays	
"Larger" LCDs (with backlight)	Merck [16], Floyd et al. [17], AEA [18], Martin et al. [19]
"Smaller" LCDs (without backlight)	Merck [16], AEA [18], Martin et al. [19]
Printed circuit boards	
Printed circuit boards originating from Cat. 1C	UNU et al. [1], AEA [18], Janz et al. [10], Rotter et al. [20], Morf et al. [21]
Printed circuit boards originating from Cat. 2	
Printed circuit boards originating from Subcat. 3A	
Printed circuit boards originating from Subcat. 4A	
Printed circuit boards originating from Subcat. 7	

[a] The distribution of individual battery chemistries was estimated from information on average marketed quantities in 1999–2001 in Germany for the period 1999–2001 [22,23].
[b] The distribution of AlMn- and ZnC-batteries respectively was assumed from the average shares (2006–2008) achieved for separately collected waste batteries in Germany [24,25].
[c] The average Hg-content was based on the amount of Hg captured during treatment of separately collected waste batteries (60 mg per kg mixed primary batteries [25] and 120 mg per kg mixed primary batteries [26]).
[d] The distribution of "toner" and "ink cartridges" was confirmed by data on empties returned for re-filling [27].

treated and components removed. Yearly records of appropriate mass balances were available for 9 treatment plants (several plants processed several waste streams and did not keep separate records for components removed from sWEEE; some kept no records for any of the components investigated in this study). The records thus obtained accounted for the processing of approximately 80% of the total Austrian sWEEE treatment mass. Seven of the plants investigated applied manual dismantling for de-pollution of sWEEE, while the remaining 2 used mechanical aggregates to break up the appliances before sorting of components containing hazardous materials and valuable scrap fractions along conveyor belts. Three of the investigated treatment plants were run as socio-economic enterprises.

For 5 plants the estimated mass of hazardous substance containing components present in treated sWEEE was calculated from the composition of appliances according to type determined by sorting analysis as described above. For the remaining 4 plants the average composition reflecting the composition of separately collected municipal sWEEE in Austria was used. In final assessment of de-pollution the calculated estimated values for the mass of individual components were compared with quantities actually removed by the respective treatment plants (rate of removal).

4. Results

4.1. Mass of components containing hazardous substances

The contents of individual components containing hazardous substances according to sub-categories, and the average mixture of separately collected sWEEE obtained from dismantling trials and sorting analyses are presented in Table 5. Additional information on the composition of sWEEE is provided in Table 6.

4.2. Hazardous substance inventory

Table 7 illustrates the contents of hazardous substances calculated for the average mixture of municipal sWEEE obtained through separate collection in Austria (average composition of 2006 and 2008) caused by the selected components. The majority of hazardous substances are allocated predominantly to a single component. As an example, Pb, Sb and brominated flame retardants originate mainly from printed circuit boards (without considering additional loads from cables and plastics). Cd and Hg are allocated primarily to batteries. PCBs are derived from capacitors. A substantial proportion of specific hazardous substances however, such as Ni and Cr, is derived from batteries and printed circuit boards. Arsenic stems from printed circuit boards as well as from LCD panels. The contribution of toner and ink cartridges to the overall pollutant content is comparably low.

It should be pointed out that the actual overall content of hazardous substances in sWEEE is higher than the figures reported due to additional loads contained in materials or components not accounted for here. Plastics and cables were not evaluated in our research, although data on contents of WEEE plastics reported by Schlummer et al. [29], Dimitrakakis et al. [30] and Morf et al. [31] indicate a substantial contribution by the contents of flame retardants, Cr, Sb and Sn. However, quantification of the contribution of plastics to overall hazardous substance content in sWEEE appears to be scarcely feasible in view of the marked variations reported in the literature references cited. The Pb-contents of cables as reported, among others, by IFEU [32] indicate a significant contribution to total lead content.

Table 5
Contents of components containing hazardous substances for an average mixture of separately collected sWEEE and for individual sWEEE sub-categories.

Component containing hazardous substances	Content in sWEEE sub-category (kg/t)					Content in average sWEEE mixture (kg/t)	
	1C	2	3A	4A	5–9		
Capacitors	6.31	1.79	3.79	4.65		3.27	0.52 kg/t originating from Cat. 2 2.36 kg/t originating from Subcat. 3 + 4A 0.39 kg/t originating from Subcat. 1C
Batteries and accumulators		2.0	3.53	0.79	6.0	2.48	1.4 kg/t Ni/Cd-batteries 0.07 kg/t button cells[a] 0.19 kg/t Ni-MH accumulators 0.54 kg/t Li-ion-accumulators 0.28 kg/t AlMn- and ZnC-batteries[b,c]
Toner and ink cartridges			3.42			1.12	1.06 kg/t toner cartridges[d] 0.06 kg/t ink cartridges[d]
Liquid crystal displays (LCDs)			1.87	4.03	3.27	1.74	0.77 kg/t "larger" LCDs (with backlight) 0.97 kg/t "smaller" LCDs (without backlight)
Printed circuit boards	2.44	1.21	95.95	101.62	3.5	52.33	0.14 kg/t originating from Cat. 1C 0.31 kg/t originating from Cat. 2 36.58 kg/t originating from Subcat. 3A 16.81 kg/t originating from Subcat. 4A 0.45 kg/t originating from Subcat. 7

Ni/Cd, nickel/cadmium; Ni-MH, nickel-metal-hydride; AlMn, alkaline-manganese; ZnC, zinc-carbon.

Table 6
Material composition of sWEEE by sub-categories (kg/t).

Subcategory	1C	2	3A	4A	5–9
Hazardous	9	5	109	111	13
Iron and steel	711	159	496	372	325
Aluminium	8	20	19	21	
Copper	41	0	9	28	
Cables	9	65	28	13	85
Plastics	127	457	313	213	103
Mixed and other metals	59	263	20	60	191
Others	37	31	6	183	283
Total	1000	1000	1000	1000	1000

4.3. Removal of components containing hazardous substances at Austrian treatment facilities

The total mass of sWEEE processed by the 9 facilities investigated amounted to 17,140 t/a on average for the years 2006–2008. Approximately 4000 tonnes thereof were imported. The average treatment mass of individual plants ranged between 26 t/a and 7000 t/a, with 5 of the plants processing more than 1000 tonnes of sWEEE per year. Table 8 illustrates minimum and maximum removal rates achieved by the latter. Furthermore, the total rate of removal (weighted average) achieved by all investigated plants is presented. In general the rate of removal varies strongly between individual facilities. However, a rather low rate of LCD panels was removed by all plants. With the exception of batteries the total removal rates achieved by the 9 treatment plants accounted for approximately half of the estimated amounts of maximum rates for the respective components. For batteries and toner and ink cartridges, maximum removal rates of individual plants exceeded 100%. This outcome may have been due to the following reasons: first, if larger selective deliveries of specific types of appliances are received from commercial and industrial sources, the characterisation of input material may not be representative. These

Table 7
Calculated hazardous substance contents (produced by the components considered) in an average mixture of separately collected sWEEE (in mg/kg).

Group of hazardous substances	Hazardous substance	Capacitors	Batteries and accumulators	Toner and ink cartridges	LCD-panels	Printed circuit boards	sWEEE
Flame retardants	TBBPA					26.9	1.46
	HBCD					10.0	0.54
	PentaBDE					27.9	1.51
	TetraBDE					26.6	1.44
	TriBDE					0.40	0.02
	OctaBDE					10.0	0.54
	DecaBDE					27.0	1.30
	4-Bromophenyl ether					0.20	0.01
Phtalates	bis(2-Ethylhexyl)phthalate					448	24.3
	Di-n-butylphthalate					1.2	0.06
Organic, others	BTEX			1.86			0.002
	PAHs			4.46			0.005
	PCBs	1170					3.82
Electrolytes from batteries and accumulators	Lithium hexafluorophosphate		12,700				31.5
	Poly(vinylidene fluoride)		3360				8.3
Metals	As				3970	19.5	7.97
	Be					3.09	0.17
	Bi					7.02	0.38
	Cd		85,500	0.018		19.6	213
	Co		52,100	2.68			129
	Total Cr		1140	34.2		605	35.7
	Hg		1390	0.297	7.7	0.938	3.50
	Li		6230				15.4
	Mn		31,200	65.8			77.4
	Ni		156,000	5.13		7630	800
	Pb		38.5	1.54		32,700	1780
	Sb					776	42.1
	Sn			11.1		5750	312
Toner dust	Toner dust			85,500			96.0
Liquid crystals	Liquid crystals				800		1.39

TBBPA, tetrabromobisphenol-A; HBCD, hexabromocyclododecane; BDE, brominated diphenyl ethers; BTEX, benzene, toluene, ethylbenzene, xylene; PAHs, polycyclic aromatic hydrocarbons; PCBs, polychlorinated biphenyls.

Table 8
Removal rates for components containing hazardous substances from sWEEE; minimum and maximum rates achieved by plants with a treatment quantity >1000 t/a, total rate of removal by all plants investigated (in % of estimated value).

Component containing hazardous substances	Rate of removal (% of estimated value)		
	Minimum	Maximum	Total rate of removal (weighted average)
Capacitors	16	86	46
Printed circuit boards	2.7	84	27
Batteries	11	>100[a]	72
Toner and ink cartridges	20	>100[a]	52
LCD panels	5.6	23	21

[a] Ambiguous results due to unknown variations in input material or in composition of removed fractions (in particular for Pb-accumulators) at a specific plant.

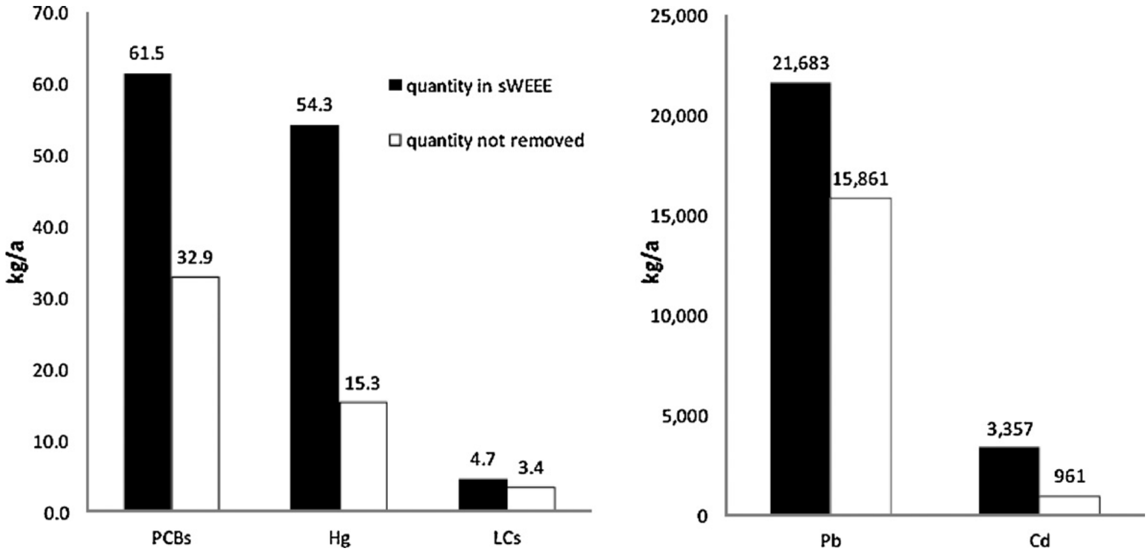

Fig. 1. Estimated quantity of selected hazardous substances in sWEEE input of and quantity removed by the 9 plants investigated (in kg/a).

deliveries are usually not documented. However, additional quantities of copying machines, printers or uninterruptible power supply (UPS) appliances might influence the quantities of toner and ink cartridges and batteries (Pb-accumulators) remarkably. Furthermore, the components actually removed at the treatment plants might contain additional quantities of other components or materials, e.g. battery pack components or other assemblies in batteries fractions.

4.4. Relevance of removal

To assess the relevance of removal of components containing hazardous substances a comparison was drawn for selected hazardous substances between the content present in sWEEE and quantities removed. Results for selected hazardous substances of major relevance are illustrated in Fig. 1. In particular for Pb, liquid crystal substances and PCBs, substantial proportions (74–54%) of

Table 9
Overview of the relevance of removal for individual components containing hazardous components from sWEEE.

Component	Hazardous substances of relevance	Legal provisions regarding hazardous substances of relevance	Relevance
Capacitors	PCBs Substitute substances (e.g. naphthalene, diethylhexylphtalate)	The marketing of PCBs has been prohibited by Regulation (EC) No 850/2004 since 2004. Austrian regulations have prohibited the production and marketing of PCBs since 1993 (FLG II 210/1993).	*Environmental impacts*: Dispersion of PCBs in the course of mechanical processing. According to the ban on PCBs a further decline is expected. Limited information on content and hazardousness of substitute substances available. *Working place exposure*: Health risks from release of PCBs and several substitute substances identified in capacitors. Limited information on content and hazardousness of substitute substances.
Printed circuit boards	(Heavy) metals (e.g. Pb, Hg, Cd, Ni, Cr, Sb, Bi, Be, As,. . .) Brominated flame retardants Organic softening agents	Pb, Cd, Hg, Cr VI, PBB and PBDE have been restricted by Directive 2005/95/EC inr appliances put on the market since 2006.	*Environmental impacts*: Dispersion of pollutants in the course of mechanical processing. Major overall source of hazardous substances in sWEEE. Several have not yet been restricted (Be, As, etc.). *Recycling*: Loss of precious metals in the course of mechanical processing of sWEEE Impacts depend on entire treatment chain for printed circuit boards (removal, mechanical processing, metallurgical processing).
Batteries	Heavy metals (e.g. Cd, Pb, Hg, Co) Electrolytes (e.g. lithium hexafluorophosphate)	Hg and Cd have been restricted by 2006/66/EC in batteries marketed since 2006 (exemption for NiCd-batteries in power-tools still effective)	*Environmental impacts*: Dispersion of heavy metals in the course of mechanical processing. Major source of hazardous substances in sWEEE. Only two are currently restricted. *Working place exposure*: Health risks from some heavy metals (Hg) and electrolytes used in batteries (formation of HF from lithium hexafluorphosphate). *Recycling*: Loss of valuable metals, e.g. Li, Co, rare earth metals.
Toner and ink cartridges	Toner dust (mainly heavy metals, Sn-organic compounds)		*Environmental impacts*: Comparably low content of hazardous substances. *Working place exposure*: Release of particulate matter. *Recycling*: Dust spread over plastic reduces identification, separation and recycling options.
LCD panels	Heavy metals (Hg, As) Liquid crystal substances	Limitation of the Hg-content of backlights by Directive 2005/95/EC in appliances marketed since 2006.	*Environmental impacts*: Comparably low content of Hg from backlight. Quantities of LCD screens will rise considerably in the future. Potential dispersion of As in shredder process. *Working place exposure*: Releases of Hg from fragile backlights. *Recycling*: Recycling of In could be relevant in the future.

PBB, polybrominated biphenyls; PBDE, polybrominated diphenyl ethers; PCBs, polyhlorinated biphenyls.

the contents estimated in sWEEE were not removed by currently applied treatment technologies. Lower proportions of Cd (29%) and Hg (28%) remaining in the sWEEE mixture may be explained by the comparably high removal rates achieved in practice for batteries.

Removal of capacitors is primarily relevant in terms of environmental loads, in view of the fact that liquids (PCBs and electrolytes) disperse into metal and in particular organic fractions and also in terms of working place exposure. For tantalum capacitors, typically used in small, high value appliances like mobile phones, the removal can also be relevant for the high economic value of tantalum. Battery removal is of particular significance in avoiding dispersion of hazardous heavy metals, such as Cd, Hg or Pb. Likewise, exposure at working place to considerably volatile heavy metals dispersed from batteries, such as Cd and Hg, as well as electrolytes such as lithium hexafluorophosphate, is also relevant; recycling is also of significant concern due to the loss of valuable metals (Co, Li). With regard to Cd and Hg the effects of limitation of heavy metal contents in portable batteries (0.0005% Hg by weight, 0.002% Cd by weight) set by the European Batteries Directive 2006/66/EC should be considered. Assuming that the batteries and accumulators present in sWEEE fully comply with these provisions the Cd-content in sWEEE mixture would be reduced by approximately 50% and the Hg-content by approximately 90%.

Removal is of lower environmental relevance for toner cartridges, although particulate matter (toner dust) imposes a health risk at working places in the recycling industry. The removal of toner and ink cartridges is also of relevance in plastic recycling as dispersed toner dust reduces the options for identification, separation and recycling. With regard to liquid crystal panels removal is of relevance in terms of environmental impacts (As, Hg) as well as for working place exposure. Although the contribution to the overall Hg-content in sWEEE by LCDs is presently rather low compared to batteries, Hg from fragile backlights is easily released and the quantities of LCDs introduced onto the market are expected to rise considerably. The content of indium in liquid crystal panels may prove to be of particular relevance in recycling in the future, in view of the very limited supply of natural resources [33].

In particular for printed circuit boards, assessment of the relevance of removal is more complex. Potential environmental impacts as well as recovery rates for valuable elements (Cu, Al and precious metals) depend on the entire treatment chain. Low removal rates of printed circuit boards may lead to the release of pollutants during subsequent shredding processes, in general undesired processes for printed circuit boards, and loss of precious metals. On the other hand, printed circuit boards which are not removed may also constitute part of the non-ferrous metal fraction in a specific treatment process with high recovery of precious metals. In a case study [34], mechanical processing of printed circuit boards from PC featured a recovery rate for gold of 70%.

Printed circuit boards removed in the first treatment step will be subjected to additional processing steps, including mechanical treatment (optional) and metallurgic processes. Potential emissions depend on the efficiency and appropriateness of the processes applied. While data on emissions from these processes are rarely available, recovery rates show a wide range. Keller [35] reported recovery rates for gold from printed circuit boards ranging from approximately 50% (leaching processes in developing countries) up to 95% in state of the art metal refineries.

A decline can be expected in the high Pb load of printed circuit boards in the future, when appliances complying with the heavy metal restrictions set by the RoHS-Directive 2005/95/EC reach the end of their life. However, no restrictions have yet been established for other pollutants such as Be and As. Details are shown in Table 9.

5. Conclusions

The results of the present study reveal how components containing hazardous substances are only partly removed during treatment of separately collected sWEEE in Austrian treatment facilities, underlining the high variation between the plants analysed. This implies that substantial quantities of hazardous substances are forwarded to subsequent mechanical treatment processes (e.g. ~9.3 tonnes Pb, 0.02 tonnes PCB or 0.009 tonnes Hg per 10.000 tonnes of sWEEE treated), causing significant dispersion of pollutants (contamination of output fractions, emissions). Easily releasable pollutants, such as Hg from LCD-backlights, Cd from batteries and highly contaminated dust in general, furthermore pose substantial health risks for plant workers. Low removal rates of printed circuit boards, batteries, and toner cartridges may also reduce quantities of valuable recyclable materials (precious metals, plastics).

The quantities of hazardous substances introduced into shredder processes reported in this paper are based on the composition of collected sWEEE. It should be borne to mind that on the one hand, overall contents of particular pollutants, i.e. those restricted by RoHS- or the Batteries Directive, are expected to decline. On the other hand, information on contents and properties of substitute substances, e.g. electrolytes in capacitors, accumulators, is somewhat lacking.

In order to minimise environmental impacts and risks for workers at sWEEE treatment facilities, the removal of hazardous components from mixed municipal sWEEE should be considerably improved. However, further research should be undertaken to identify optimum treatment of the components removed, in particular for printed circuit boards. Furthermore, for mechanical pre-treatment of sWEEE with subsequent sorting of components containing hazardous substances, the potential release of pollutants should be investigated in the first treatment step. Finally, it should be taken into account that a substantial part of sWEEE is not collected separately but ends up as residual waste and in mixed metal scrap.

Although no comparable studies have been performed in other European countries, the results obtained reflect the state of depollution of sWEEE in Austria, indicating the need for measures to be implemented to ensure the achieving of sufficient levels of de-pollution during sWEEE treatment.

Accordingly, the method applied should be further optimised and improved. The use of larger samples of input material in the calculation of estimated values of components containing hazardous substances would – by reducing statistical uncertainty as to the composition of types of appliances – increase accuracy of the comparison of estimated and measured values. Furthermore, a wider availability of detailed data concerning WEEE treatment, particularly focusing on mass balances on a yearly basis (not extrapolation based on batch trials), and documentation of the presence of non-household appliances or untypical appliances in input material would increase the significance of results.

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