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Greening of Electronics

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Indhold

Preface

The present report was drafted during 2011 and is the first attempt to describe the state of the art of the management of Waste from Electric and Electronic Equipment (WEEE) in Denmark, with specific focus on the concerns related to the presence of hazardous compounds in WEEE and resulting risk of emissions from the WEEE management system.

The initial scopes of such research were to:
- report the substances that potentially constitute a risk for humans and ecosystem during WEEE handling from collection to disposal (excluding the substances already restricted in the RoHS directive);
- report on substance, material and WEEE fractions flow analysis, emissions estimations and risk evaluation.
- identify resources and substances valuable for recovery, which can constitute an incentive for a more intensive sorting and recycling of WEEE.

However, covering completely these scopes demonstrated to be an ambitious task considered the presently available information on WEEE. The report presents therefore an overview of the Danish WEEE management and reporting system. Specific data and information on the WEEE flows, fractions and composition, which are needed for estimating treatment–related hazardous emissions and subsequent risks towards humans and the environment, are presented. Material and Substance flow analysis are presented as well. Significant gaps and uncertainties on content of HS in Danish WEEE information do not allow for quantitative risk estimates for environment or human health.

The report provides useful information regarding the general shortcomings of the actual WEEE management system in Denmark and regarding the specific concerns related to the presence of hazardous substances in Danish WEEE. The report presents the first quantitative assessment of mass and substance flows within the Danish WEEE system and constitutes an important and solid base for further analysis and research on WEEE.

Sammenfatning og konklusioner

Håndtering af affald af elektrisk og elektronisk udstyr (WEEE) kan potentielt give en effekt på mennesker og miljø på grund af tilstedeværelsen af farlige stoffer i WEEE. Dette projekt har til formål at identificere yderligere problematiske stoffer i WEEE affaldssystemet, samt barrierer for genanvendelse. Rapporten giver et overblik over det danske WEEE-system; herunder information om indsamling og behandling af WEEE fraktioner i Danmark samt indholdet af farlige stoffer i WEEE systemets affaldsfraktioner. Der er udarbejdet en massestrømsanalyse på et shredderanlæg som betragtes repræsentativt for Danmark.

Efter en litteratur review på viden om indholdet af problematiske stoffer i WEEE, er der endvidere udarbejdet en stof flow analyse for udvalgte problematiske komponenter i WEEE med fokus på stoffer som ikke er opført RoHS. Desuden er den tilgængelige viden omkring de potentielle humane og miljømæssige konsekvenser i forbindelse med potentielle emissioner fra WEEE behandlingssystemet præsenteret, samt de økonomiske drivkræfter og barrierer for genanvendelse og / nyttiggørelse af WEEE til energiproduktion.

Rapporten diskuterer endvidere kvaliteten af den statistiske opgørelse af WEEE strømme i DK, bekymringer vedrørende bl.a. beryllium og bromerede flammehæmmere i WEEE, usikkerhed og manglende data i relation til eksponering og konsekvensanalyse af det danske WEEE behandlingssystem.

Summary and conclusions

This report presents an overview of the Danish Waste from Electric and Electronic Equipment (WEEE) management system, including data on EEE production and WEEE collection and treatment in Denmark. The management of WEEE may potentially produce an impact on humans and environment due to the presence of hazardous substances in WEEE. Except from the substances already regulated by the EU directive on the restriction of hazardous substances (RoHS directive) in WEEE, other compounds that can be found in WEEE may be of concern. However, knowledge of the content of hazardous substances within individual WEEE fractions is scarce and no monitoring of emissions from the treatment processes exists.

Material flow analysis of WEEE fractions within a Danish WEEE pre-processing facility is presented, representative for the type of WEEE treatment occurring in Denmark and up-scaled to national level. A literature review with focus on hazardous substances of concern and not included in the RoHS directive have been performed and used as input a subsequent substance flow analysis for hazardous compounds inside the WEEE management system. No data on emissions from WEEE treatment processes are available and in general data are extremely few. As such it is not at the moment possible to estimate emissions and resulting potential human and environmental impacts related to WEEE treatment.

Gaps in accounting for WEEE flows in the actual management system, economic drivers and barrier for recycling and/ recovery of WEEE for energy production, and the concerns related to hazardous substances in WEEE and the uncertainties and data gaps in exposure and impact assessment for WEEE treatment, with specific reference to the Danish context, are presented and discussed. Identified hazardous compounds that are not regulated by RoHS like are: Beryllium, Indium Phosphide, Gallium Arsenide, Americium, Germanium, Antimony trioxide, Brominated Flame Retardants (TBBP-A and HBCDD).

1 Introduction

Electrical and Electronic Equipment (EEE) may include substances that have adverse effects on human health or cause damage to the environment. Further, waste from EEE (WEEE) is the fastest growing waste fraction in Europe. Thus it is essential to have a proper WEEE management system in place. The European Community Directive 2002/96/EC on Waste Electrical and Electronic Equipment (the WEEE Directive), together with the European Community Directive 2002/95/EC on the Restriction of Hazardous Substances (the RoHS Directive) were established to meet this objective. The WEEE Directive sets collection, recycling and recovery targets for ten types of EEE. The RoHS Directive restricts the use of six hazardous substances; lead, mercury, cadmium, hexavalent chromium and polybrominated biphenyls (PBB) and poly-brominated diphenyl ethers (PBDE).

However several studies (e.g. Environment Canada, 2004; Öko-Institut e.V., 2008) indicate that other substances present in EEE may also have adverse effects on human health or cause damage to the environment.

Potential emissions from the management of WEEE may be divided into three main types (Schluep et al., 2009). Primary emissions of hazardous substances that are contained in WEEE like lead, mercury, beryllium, indium, antimony, arsenic or polychlorinated biphenyls (PCBs). Secondary emissions of hazardous reaction products of WEEE substances as a result of e.g. incineration of plastics containing brominated flame retardants such as the PBDEs resulting in unintentional emissions of dioxins. Tertiary emissions including hazardous substances or reagents, such as cyanide or other leaching agents or mercury for gold amalgamation, that are used during recycling processes.

The primary emission may be directly regulated by restricting the use of specific hazardous substances in EEE, as in the case of the Directive 2002/95/EC. The two remaining types of potential emissions occur as a result of a specific WEEE treatment process, and therefore vary according to the life cycle of each individual substance within the WEEE management system. In order to reduce and avoid these potential emissions, it is necessary to regulate and control the treatment processes, e.g., by the application of air-pollution control devices in thermal treatment plants or restrict combustion of certain problematic waste fractions (Thomsen et al, 2009). The handling and treatment of WEEE have an increased potential for emission of hazardous substances compared to other waste fractions; this eventually leading to risks of impacts on the environment and on human health.

The present report focuses on the primary emissions by quantifying the flows of hazardous substances occurring during the treatment of WEEE in Denmark, and by describing potential exposure pathways, whereas the secondary and tertiary emissions are only briefly discussed. Further, the use of hazardous substances in EEE may prevent or increase the expenses in relation to potential recycling of materials leading to substantial loss of income and economic incentive for recycling companies, collective scheme actors and producers. The objective of this project is to present existing knowledge on the life cycle of hazardous compounds and to identify problematic waste fractions or flows including hazardous substances present in EEE and not yet regulated in the RoHS directive. Further, to analyse their potential routes of emissions within the Danish WEEE management system as well as barriers for recycling and/or recovery of WEEE fractions due to the content of these hazardous substances.

Chapter 2 presents an overview of the how the WEEE directive has been implemented in Denmark with focus on actors and responsibilities within the Danish WEEE management system. Chapter 3 gives a presentation of the EEE-WEEE flows within this system according to DPA-system representing, so far, the national entity collecting and reporting national WEEE statistics required according to the WEEE directive. Chapter 4 presents the analysis of WEEE fraction material flows within a Danish WEEE pre-processing facility. Chapter 5 reports existing knowledge of the content of hazardous substances and precious metals within WEEE fractions, and provides knowledge on the hazardous substances of concern not regulated by the RoHS directive. In Chapter 6 the material flows and the concentration levels of hazardous compounds previously presented (Chapter 4 and 5) are used as input data in a quantitative substance flow analysis for hazardous substances in the Danish pre-processing facility and at national level. Chapter 7 describes qualitatively, and in a Danish context, the potential exposure to hazardous substances in WEEE. Chapter 8 discusses the economic drivers and barrier for recycling and recovery and, lastly, Chapter 9 presents the conclusions.

2 Actors within the Danish WEEE management system

This chapter gives a general description of how the WEEE Directive is implemented in Denmark. The WEEE directive sees to achieve its objective using the concept of an extended producer responsibility, where in principle the producers are responsible for a circular EEE-WEEE-EEE management system.

Producers are defined at national level in the Danish Statutory Order No. 362. Producers and importers (or distributors) of EEE are obligated to:

- Register with the competent authority nominated by each EU member state to track producer compliance and provide estimates of the weight of equipment intended to be put on each national market annually
- Arrange acceptable financial guarantees to meet obligations arising in each member state
- Ensure that appropriate data is collected to be able to demonstrate compliance in each relevant member state.
- Ensure that the WEEE is collected and managed by an approved processor.

In Denmark, the competent authority nominated to administer the WEEE regulation, including registration and reporting, is DPA-system (Danish Producer Responsibility System (DPA-System, www.dpa-system.dk).
In detail, the producer duties are:

- Register to the DPA-System Producer Register, giving detailed information on product categories and labels.
- Collect WEEE from private households at the municipal recycling stations in accordance with instructions given by DPA-System.
- Collect WEEE from trade and industry at their customers, or make an agreement with their customers on transfer of the producer responsibility.
- Make sure that the WEEE that is collected undergoes special treatment at an authorised treatment facility.
- Inform treatment facilities about reuse and treatment of the products.
- Pay all costs of transport and treatment of WEEE.
- Provide security for future costs for transport and management of WEEE from private households.
- Report data on volumes to DPA-System regarding marketed products and WEEE that has been collected.
- Assume collective responsibility for WEEE from private households that was marketed before 1 April 2006 (”historical waste”).

In summary, producers and importers of household EEE products (Business-to-Consumer Producers) have the responsibility of registering, reporting and taking back their products. However, they can either assume duties individually (individual compliers) or they can transfer some of the tasks under the producer responsibility to a so-called collective scheme. In fact, the

obligations on the producer to inform the treatment facilities about reuse and treatment of the products and the obligation to report on volumes to DPA-System regarding marketed products and WEEE that has been collected are in most cases realised by a partnership with one of such collective compliance scheme organisations in Denmark.
DPA-System estimates the amount of WEEE to be recovered at each municipality via the municipal collection system. Based on this, DPA-System assigns collection sites and WEEE fractions to the collective scheme actors according to the market share of the member producers in each collective scheme. The assignment takes into account both amount and type of equipment put on the market by their member producers; hence the different collection fractions are assigned to different collective scheme actors within the same municipality.
Reported data by individual producers or a collective compliance scheme organisation forms the basis for WEEE-statistics reported each year (e.g. DPA-system, 2010) by DPA-System since 2007 documenting Denmark's compliance to the WEEE objectives. From 2006, producers are obliged to pay a fee to DPA-System for administrating and reporting of WEEE statistics.

The WEEE management system consists of three steps:

1. Collection
2. Sorting/dismantling and pre-processing, incl. mechanical treatment such as shredding
3. End-processing, incl. refining of recycled materials and disposal

Step 1 and 2, and the part of step 3 referring to disposal by land filling and thermal treatment, takes place in Denmark. Refining and recovery of value carrying resources from recycled materials occurs outside Denmark.
Figure 1 visualises the information flow and collaboration network of the actors within the Danish WEEE management system.

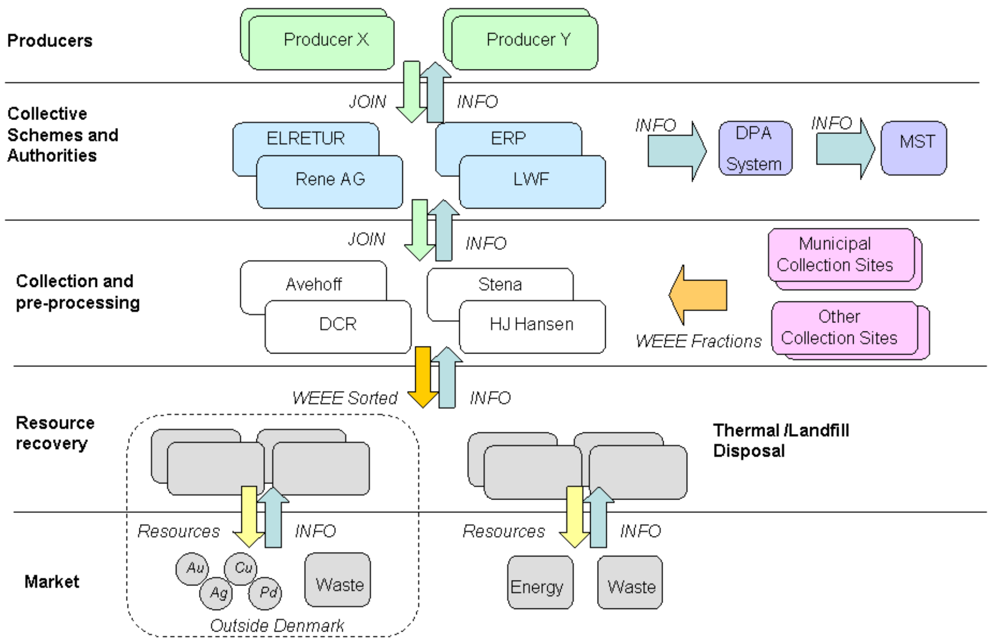

Figure 1 Principal actors within the WEEE management system inside Denmark and resource flow for recycling outside Denmark.

2.1 Collection

It is important to note that products are distinguished between household (Business-to-Consumer, B2C, producer) and professional (Business-to-Business, B2B, producer) products. In Denmark the physical infrastructure and financial responsibility for collecting WEEE from private households are allocated to the municipalities providing collection sites where the consumers can deliver their end-of-life household products. These are sorted in different fractions at the municipal collection sites. In turn, the producers collect the fractions, via a collective scheme organisation, who on behalf of the producers take responsibility for the end-of-life management. The responsibility of B2B producers may be handed over by labelling the products with an end-of-life stage management instruction. Collection of WEEE from the business sector may occur at private collection sites operated by companies which may or may not be part of a collective scheme organisation (denoted as 'other collection sites' in Figure 1) such as e.g. the company Jernpladsen (www.jernpladsen.dk). It is valid the principle that professional products in quantities and types comparable to household products can be collected via the municipal system. Detailed info on products and exceptions to the rule may be accessed at http://www.dpa-system.dk.

2.1.1 Municipal collection sites

At the Danish municipal collection sites the collection is carried out in 5 fractions as the products in each fraction are believed similar enough to pass into the same treatment (Sorting/dismantling and pre-processing). The relation between the 10 categories in the EU directive and the 5 separately collected fractions at the Danish municipal collection sites is listed in Table 1.

Table 1 Danish collection fractions and the WEEE categories (BEK nr 362 of 06/04/2010)

WEEE category*	Danish collection fractions
1	1. Large household appliances and automatic dispensers
2, 6, 7, 8, 9	2. Small household appliances and others
3	3. IT & telecommunications equipment
4	4. Consumer equipment
5	5. Lighting equipment

*Category 10 is not considered as household product (DPA Statistics, 2009)

The five fractions are stored in cages, pallets and containers which eases the transport for further treatment at different recycling companies. Five different companies, representing the collective scheme, are assigned by the DPA-System to collect and treat each individual collection fraction within a municipality. The collective schemes may in turn hire recycling companies to be responsible for the further transport and treatment of individual categories in and outside Denmark. As such the collective schemes play a major role in realizing Denmark's compliance to the WEEE directive.

2.1.2 Other collection sites

The recycling companies may collect e-waste from with private collection sites in addition to the municipal collection sites. Private collection sites may receive smaller amounts of WEEE from private households, public institutions, as well as larger amounts of WEEE, e.g. from sales stores and supermarkets, taking back old products (e.g. www.jernpladsen.dk). Furthermore, the sites can accept business WEEE. To the extent that these sites are owned by the producers themselves, they have the same obligations to report to DPA-system as if they were partner of the collective scheme.

2.2 Collective scheme

Producers report to DPA-System via the collective scheme in which they are part of. In this way they have only one contact point taking care of the logistics of the whole EEE-WEEE. From the point where the collective scheme has been assigned of different municipal collection sites, where they have to collect one or more WEEE categories, they have taken over the producer responsibility regarding documentation of the remaining WEEE treatment processes. As such the collective scheme is responsible for the compliance to the WEEE directive regarding the further treatment and recycling of business and household WEEE. The collective scheme actors have their own vehicles or hire recycling companies to collect WEEE at the municipal collections stations and the schemes are obliged to inform the producers of the final treatment of the recovered products for which they are responsible. B2B Producers of non-household EEE can self-comply with the WEEE Regulation and as such they may collaborate with recycling companies, which are not members of the collective scheme and therefore not obliged to report to DPA-system. After implementation of the new Waste directive in September 2010, private companies like Jernpladsen do report their collected and treated WEEE categories and amounts (www.jernpladsen.dk).

The collective scheme organizations in Denmark must register their members within the national register held by DPA-System. The information registered for the enterprise, which is a member of one of the collection scheme organizations, is the same as the information registered for the individual producers. This is also the case for the annual reporting (DG. ENV., 2007).
Currently, there are various different collective scheme actors in Denmark: Elretur, ERP (European Recycling Platform), RENE AG (Recycling Network Europe), and LWF (Lyskildebranchens WEEE Forening). These collective scheme organizations act as competing actors in the Danish market, with the EEE producers as customers. A producer can decide to join one or the other collective scheme actors according to the quality of the quality of the reporting service provided. The use of a visible fee for financing of the management of historical WEEE is optional (DG. ENV., 2007).

2.2.1 Elretur

Elretur is a collective scheme that “works on a non-profit basis for its members and has no financial interests in its own right” (www.elretur.dk) and that modelled on the Swedish system El-kretsen (www.el-kretsen.se). El-kretsen is a monopoly that collects almost all WEEE in Sweden and imposes e.g. that the participating recycling companies live up to certain recycling efficiencies. The producers that join Elretur pay a yearly membership fee and the revenues are used by the organization to cover costs of collection and treatment of waste equipment. Elretur does not have recycling facilities or collection vehicles of their own. Instead, there is a tender, which is regularly renewed, to determine who is awarded the business of collecting and treating the waste. Elretur collects 2/3 of the WEEE at the municipal collection sites (personal communication, Henrik Jacobsen, Elretur).

2.2.2 ERP - European Recycling Platform

ERP is a competing scheme to Elretur, RENE and LWF. It was originally established by some of the major producers (Braun, Electrolux, HP, and Sony Europe). It was established as a direct action against having only Elretur as a monopoly (DPA-System, 2010a). It has fewer members than Elretur and according to Elretur; ERP collects 1/3 of the WEEE from the Danish municipal collection sites, which are treated outside the country (personal communication Henrik Jacobsen, Elretur). The payment model in ERP is a "Pay-as-you-scrap" model where the producers pay their share of the recovery/recycling costs depending on their annual product sale (http://erp-recycling.dk/)

2.2.3 RENE AG – Recycling Network Europe

RENE is a Europe's biggest commercial network of e-scrap specialists with 57 sites in 19 countries and an annual capacity above 800.000 ton per year. RENE AG runs compliance schemes in Denmark (DPA-System, 2010a). A central element of the RENE AG is the possibility for producers to opt out individual quantities and dedicate them to recycling partners of their own choice. Solely the invoicing for logistics and recycling always goes over RENE AG. RENE AG either run individual take back schemes or performs the interface to existing schemes (http://www.rene-europe.com).

2.2.4 LWF

LWF (Lyskildebranchens WEEE Forening) is a collective scheme covering only lighting products. Hence, they are only assigned the collection of category 5 WEEE.

2.3 Sorting/dismantling and pre-processing

Recycling companies are hired by the collective schemes to collect one or more of the five fractions at each municipality. The recycling companies handle the WEEE according to the WEEE directive, i.e. removing components, emptying cooling liquids, removing displays etc.

The processes taking place in Denmark are collection, sorting/dismantling and pre-processing (e.g. shredding); step 2 including removal of materials and components as specified in Annex 3 and 4 in the WEEE directive. The sorting/pre-processing is a combination of manual and automatic processes varying from company to company. The automatic processes include the downsizing of material in shredding equipment followed by a material sorting. The automatic sorting is dividing the WEEE into a ferrous fraction using electromagnetic separation, a non-ferrous metal fraction using e.g. eddy current separation, and a residual fraction. Some recycling companies also send products directly to treatment in e.g. Sweden or Germany. At Averhoff A/S the automatic sorting is done on smaller parts (below 10x10cm) and a manual sorting is performed on the larger parts (see Table 2).

There are no resource recovery companies in Denmark. Instead, the sorted fractions are sent to further resource recovery and recycling, e.g., in Germany or Sweden. The Danish recycling companies receive information on the recycled resources from the receiving foreign country companies handling the further recycling. This information is relayed to DPA-System.

Table 2. Extract of assigned municipal collection sites, collection fractions and assigned collective schemes; Elretur in green, ERP in blue, RENE AG in purple and LWF in red. The name of the recycling companies that are responsible for the treatment is in parenthesis. (Source: DPA.-System, 2009).

Municipality No.	165	201	420	151	530
Municipality name	Albertslund	Allerød	Assens	Ballerup	Billund
Collection point ID:	271, 273	379	28, 92, 93, 100, 104, 418	270	103, 106, 290
WEEE Fraction 1	Elretur (HJ Hansen)	RENE AG (Ragn-Sells)	RENE AG (Ragn-Sells)	Elretur (HJ Hansen)	Elretur (HJ Hansen)
WEEE Fraction 2	Elretur (DCR Miljø)	RENE AG (Ragn-Sells)	RENE AG (Ragn-Sells)	Elretur (DCR Miljø)	Elretur (Averhoff)
WEEE Fraction 3	ERP (Stena Technoworld)	RENE AG (Ragn-Sells)	RENE AG (Ragn-Sells)	ERP (Stena Technoworld)	RENE AG (Ragn-Sells)
WEEE Fraction 4	Elretur (DCR Miljø)	RENE AG (Ragn-Sells)	RENE AG (Ragn-Sells)	Elretur (DCR Miljø)	Elretur (Averhoff)
WEEE Fraction 5	Elretur (Stena Miljø)	LWF (Stena Miljø)	ERP (Stena Technoworld)	Elretur (Stena Miljø)	Elretur (Stena Miljø)

Table 2 shows the municipalities (Municipality No. and Municipality name), the numbered collection sites (Collection point ID) and the five collected WEEE fractions (WEEE Fraction 1-5). The parentheses below the collective schemes show the operator hired to do the actual collection and treatment in Denmark; HJ Hansen, DCR Miljø, Stena Technoworld, Stena Miljø, Ragn Sells and Averhoff. Operators may be private or, as in the case of DCR Miljø, owned by the municipalities.

2.3.1 Treatment inside and outside Denmark

Investments and technology requirements are less challenging in collection and dismantling, whereas mechanical pre-processing and especially the final metal recovery requires considerable investments in advanced technologies. The consequence is that for most countries only collection, dismantling and partly mechanical pre-processing takes place at a national or regional level

(Schluep et al., 2009) which is also true for Danish conditions. Treatment of complex materials such as circuit boards, batteries, or cell phones in integrated metal smelters or specialized battery recycling plants takes place in a global context. Currently, such integrated smelters with the appropriate off-gas and effluent treatment are located in Belgium, Canada, Germany, Japan and Sweden (Schluep et al., 2009).

3 Danish WEEE statistics

The DPA waste statistics are divided in two main categories; products marketed and sold to respectively households and businesses. The total amounts of EEE marketed and collected, and WEEE treated in 2006-2009 is reported in Table 3 (DPA-system, 2009).

Table 3 EEE amounts marketed and collected and WEEE treated (values in tons), period 2006-2009.

	Household	Industry	Total
EEE marketed			
2006*	123,771	29,282	153,053
2007	130,944	34,878	165,821
2008	125,801	29,151	154,952
2009	118,189	28,459	146,649
EEE collected			
2006*	51,532	1,360	52,893
2007	77,533	1,260	78,793
2008	75,082	1,335	76,417
2009	82,642	1,626	84,268
WEEE treated (inside and outside DK)			
2006*			47,468
2007			77,436
2008			76,410
2009			83,393

*only 9 months of year 2006 are considered

Table 3 shows a general trend for the marketed amounts, reported in the statistics, to be much higher than the collected amounts. Further, the amount sent for treatment is slightly lower than the value for total WEEE collected from households and industry.

The difference between marketed and collected amounts may partly be due to products being delivered directly at recycling facilities. These amounts are not accounted by the collecting schemes and are thus not reported in the official DPA statistics on collected WEEE. An example is the accredited recycling company Marius Pedersen that collects WEEE mainly from industry and does not report amounts to DPA-System (Personal communication, Ulf Gilberg DPA-system, 2010). The reason for the latter is that statistics reported by the DPA-system only partly covers business-to-business WEEE flows, whereas data on WEEE flows collected at the municipal collection sites, i.e. by members of the collective scheme, are fully covered by DPA-system (cf. Chapter 2.1).

Another explanation for the gap between marketed and collected amounts may be due to stockpiling (informally called ‘attic-effect’) where old used products are stored away instead of being disposed (Wagner, 2009). Assuming the stockpiling to be the only explanation for the gap between marketed EEE and collected WEEE in Denmark, i.e. dividing the difference between yearly marketed and collected amounts with 5.5 million inhabitants, would require an accumulation of household WEEE within the Danish homes corresponding to 10-15 kg/y/person. This would equal 40-60 kg for a family of four people each year, which appear to be an unrealistic high figure.

The contribution of stockpiling may be much less significant than the contribution of unregistered WEEE being disposed directly by industry in explaining the gap between marketed EEE and collected WEEE (Personal communication, DPA-System, 2010). This is supported by the fact that the ratio between marketed and collected amounts of industrial WEEE in the national statistics are small compared to the ones of household WEEE (around 50% for household products versus ca. 5% for business products, directly computable from table 3).

The gap between marketed and collected amounts according to the DPA-statistics is thus most likely due to an incomplete reporting system as WEEE fractions being directly collected at private collection and recycling sites such as Marius Petersen, which collect mainly WEEE originating from the B2B producers, as well as Jernpladsen, which collects WEEE from originating from B2C as well as B2B producers, are not fully reported to DPA as they are not part of the collective scheme managing the EPR in Denmark.

Lastly, consumer's behaviour may contribute to the gap to the extent that they may throw away their small EEE into their private containers collected as municipal household waste and therefore sent for combustion at incinerations plants, as in the case of small appliances like mobile phones (Ongondo, F., 2011).

The geographical location of the treatment of the collected WEEE is shown in Table 4 below. Considering the WEEE fractions included in the DPA-statistics, in total across the 10 product categories 79% is sent to treatment in Denmark, 21% in the rest of EU and 0.02% outside EU. As described in Chapter 2 the treatment within Denmark includes sorting, dismantling, pre-processing, together with the disposal of the residual fractions from sorting. The actual material recovery occurs outside Denmark.

Table 4 Treatment of WEEE, year 2009, values in tons (Source: DPA statistics, 2010). Data are reported per WEEE category in the nomenclature of the EU WEEE directive.

Year 2009 – values in tons	Treated in Denmark	Treated outside Denmark in EU	Treated outside EU	Total
1. Large household appliances	37,092	3	0	37,095
2. Small household appliances	5,500	187	0	5,687
3. IT & telecommunications equipment	5,537	8,871	0	14,408
4. Consumer equipment	14,345	7,816	18	22,179
5A. Lighting equipment – luminaries	4	0	0	4
5B. Lighting equipment – light sources	317	321	0	638
6. Electrical and electronic tools	2,308	0	1	2,309
7. Toys, leisure and sports equipment	880	0	0	880
8. Medical devices	122	2	0	124
9. Monitoring and control instruments	69	0	0	69
10. Automatic dispensers	0	0	0	0

For the purposes of calculating compliance with the targets for collection, reuse and recycling set by the WEEE directive, producers, business customers or third parties acting on their behalf are required to keep records on:

A. the total weight of WEEE entering treatment facilities,
B. the total weight of whole appliances which are re-used for their original purpose,
C. the total weight of components, sub-assemblies and consumables which are re-used for their original purpose or recycled,
D. the total weight of WEEE where energy is recovered in a power plant (incinerated WEEE)
E. the total weight of remaining WEEE which is disposed to landfill

The WEEE re-use and recycling target level may be calculated according to C/(A-B), whereas the target level of WEEE recovery may be calculated according to (D+C)/(A-B). However, such calculations are not included in the yearly statistics published by DPA-system (e.g. DPA-system, 2009).

Such data can be used in material flow analysis to calculate mass balances for the different WEEE fractions. If the composition of A and/or B, C, D, E in terms of hazardous or precious substances is known, the data can be used in a substance flow analysis to determine the total flow of substances through the treatment system and the amount that is sent to recycling/disposal. Examples of this calculation are presented in chapters 4 and 6 respectively with reference to a Danish pre-processing facility (cf. Chapter 4).

For the national situation in Denmark, information on the total weight of WEEE entering the treatment facilities, i.e. A, is available from the national WEEE statistics (Table 2), whereas information on point D and E may be calculated based on figures found in green accounting reports of the individual recycling companies. No data are available at national level or sub-national level regarding B and C. Only data on the amount of WEEE exported to other countries are available from the national DPA statistics.

Article 8(2) of the WEEE Directive 2002/96/EC(1) states, 'For products put on the market later than 13 August 2005, each producer shall be responsible for financing the operations referred to in paragraph 1 relating to the waste from his own products'. The responsibility for financing the operations related to step 2 of the WEEE management system are allocated to the collective scheme who are obliged to report back to the producers on the further treatment of the WEEE. However, this information is not included in the DPA statistics.

Improvement regarding the completeness and transparency of the WEEE management system is expected as a result of the new Danish waste directive (www.mst.dk and www.dakofa.dk).

4 Material flow analysis of WEEE fractions in a Danish pre-processing facility

In the current project the Averhoff recycling facility is taken as case study. Averhoff provided a complete and detailed data set regarding flows (mass over time) and types of WEEE treated at the facility, which can be considered as representative for the typology of WEEE treatment occurring in Denmark. The treatment processes occurring at the facility are described qualitatively in this chapter, and quantitatively by means of a simple material flow analysis. The material flow analysis highlights and quantifies the most significant output flows of WEEE fractions sorted at the facility, and describes what kind of further treatment is expected for different WEEE output fractions. A substance flow analysis for specific hazardous substances is then presented in Chapter 6. Data refer specifically to the facility under analysis and do not refer to national statistics like as presented in table 3 and table 4. The analysis is therefore focused on the local scale and not on the national, due to the limited data availability for the national scale. Data are reported respecting the privacy requirements expressed by the company.

4.1 The Averhoff recycling facility

The Averhoff recycling facility is located in Risskov, Århus, acting as a recycling company for the collective scheme, Elretur. The Averhoff facility is treating the Danish collection fractions: no. 3 - IT & telecommunications equipment, no. 4 - Consumer equipment, and small amounts of fraction no. 2 - Small household appliances and others (Cf. Table 1). The WEEE treated originates almost entirely from the municipal collection (B2C producers), and only minor quantities of waste from the business sector (B2B producers). In 2010, around 8000 tons of Cathode Ray Tubes (CRT) appliances, i.e. technology units separated from computer monitors and televisions, and around 8000 tons of other small appliances were treated at the facility.

The equipment is collected at the municipal collection sites in metal cages. The collection trucks operate with forklifts that weigh the equipment already when loading it onto the truck at the collection site. The whole truck is weighed on a weighbridge when arriving at the Averhoff recycling facility to ensure that no material is lost during the transport operations, e.g. by illegal scavenging. At the facility, WEEE is stored in cages. While unloading these cages are placed outside, waiting for the further treatment of the WEEE. A layout of the treatment processes taking place inside the recycling plant is visualised in Figure 3. The following sections provide a 'chronological' description of the WEEE flow and treatment inside the facility.

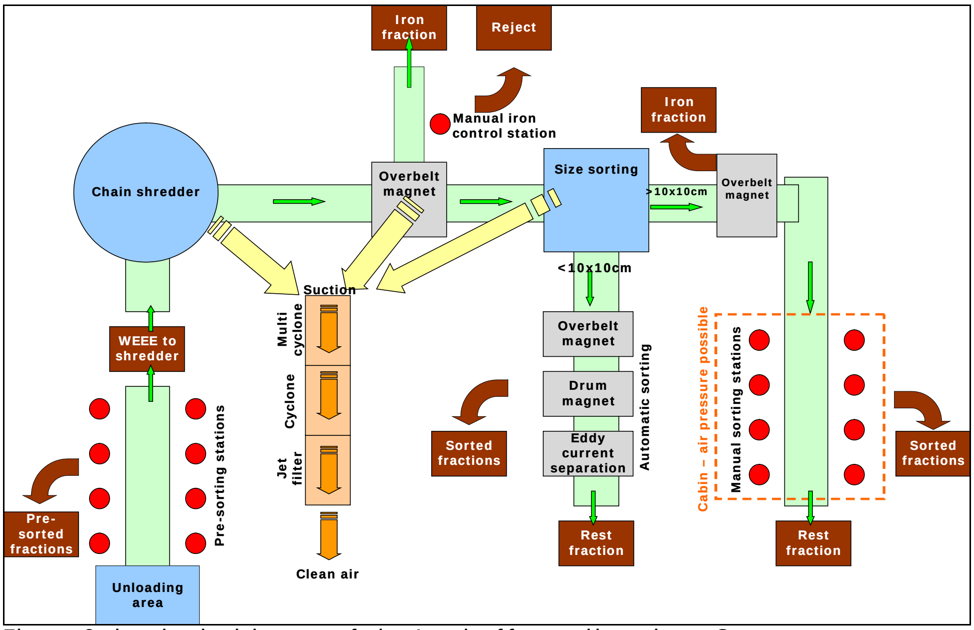

Figure 2 the physical layout of the Averhoff recycling plant. Green arrows represent conveyer belts.

4.2 Unloading and manual pre-sorting

The cages are registered before unloading. The equipment is unloaded automatically in an enclosed area to avoid personnel accidents and to reduce noise. The equipment enters a conveyer belt and passes in front of manual pre-sorting stations, each worker collecting one or more fractions each. Many different waste fractions are separated in the pre-sorting phase; these are listed in Table 5. The criteria for the sorting and the materials and components to be pre-sorted are listed in the annex II of the WEEE directive. These are materials/components that contain hazardous substances like e.g. batteries, mercury containing components, etc. (cf. Table 5). The workers at the facility know that each material/component like e.g. a television or even a specific kind of plastic material may contain hazardous substances because of labelling, because it is specifically mentioned in the WEEE directive, or because of direct communication with the EEE producers or with other pre-processing facilities. In fact, when e.g. a new material/component is found, which composition is unknown or which is suspected to contain hazardous substances, workers contact the producer or other facilities to obtain information about its composition and be able to sort it accordingly. At this level, the information about the hazardous content of WEEE is therefore only generic and not very specific, as the chemical composition of the WEEE is not analysed in detail with chemical-analytical methods. The air flow in the unloading and pre-sorting area is unregulated but with plenty of open space. The workers wear the necessary personal protective equipment. It should be mentioned that Averhoff fulfils a social responsibility by employing workers in a variety of job activation efforts.

Table 5 Pre-sorted fractions at Averhoff in accordance to the WEEE directive

Group	Sorted fraction*
Screens	Pressurized tubes, e.g. TVs
	Flat screens and laptops
Batteries	Products with embedded batteries
	Lead (Pb) batteries
	Nickel-Cadmium (Ni-Cd) batteries
	Rechargeable batteries
Mercury and radioactive containing products	Certain telephone receivers containing mercury switches
	Certain old vacuum cleaners
	Radioactive equipment e.g. old smoke alarms
Printed wiring board products	Easily removable printed wiring boards are removed
	Mobile phones
	Entire PCs
Lighting products	Energy saving light bulbs
	Fluorescent tubes
PCB	PCB capacitors
Products disturbing the shredding equipment	Light chains
	Vacuum cleaner tubes
Cables	Cables (The plugs are removed afterwards to increase the copper content)
Various	Concrete speakers
	Oil radiators
	Air condition equipment
	Printer cartridges and toners
Residual fraction (WEEE to shredder)	The residual fraction is now ready for the shredding process.

* Only the main sorted fractions in each group are listed.

4.3 Shredding

The residual fraction that can't be manually separated in the pre-sorting stage is sent to the shredder automatically via the conveyer belt ('WEEE to shredder' fraction in Figure 2). The shredder is a rotating chain crusher type with an adjustable exit hole determining the size of the material leaving the shredder. The material is slightly heated in the shredding process, up to an estimated 15-35°C, but never too hot to handle by hand. The humidity is expected to be the same as the background humidity or slightly above if the products are wet from rain. Extractors in the shredder remove small light components and are integrated with an air filtering system. The air passes through three filters, as illustrated in Figure 3.

4.4 Primary magnet sorting

The material leaving the shredder passes an over-belt magnet. Air suction is connected to the same filters as the shredder. The sorted iron fraction passes a manual check station where a) non-iron materials and b) materials that belong to other sorted fractions are rejected. Examples of rejected material are copper-containing cables or intact items containing hazardous compounds (like e.g. batteries). These are removed via manual check and collected together with their respective pre-sorted fractions. Other rejected materials are products that resisted to the shredding, and need therefore to be re-shredded.

4.4.1 Size sorting

The size sorting equipment shakes and sifts the material into two fractions; larger and smaller than e.g. 10 x10 cm; fractionation may be adjusted according to the WEEE category handled. The small fraction enters the automatic sorting line and the large fraction enters the manual sorting line. Air suction is led through the filters.

4.4.2 Filters

The air suction from the shredder, the first magnet and the size sorting passes through three filters; a multi-cyclone filter, a cyclone filter, and a jet filter. The multi-cyclone filter takes out the largest fractions, e.g. video tape, paper, carbon and small pieces of WEEE with a generation of approx. 500 kg/month. A photo of the fraction is seen below in Figure 3. The cyclone filter takes out the smaller fractions e.g. dust and fluff, similar to the dust collected in a standard household vacuum cleaner. The generation is approx. 400 kg/month. A photo of the fraction is seen below in Figure 4. The output from the multi-cyclone and cyclone filters is sent to incineration (cf. chapter 4.8) when running low-grade material through the shredder. When the feed material is high-grade material like PCs the dust is considered valuable in monetary terms and is sent to recycling for metal extraction instead of being incinerated.

Figure 3 Output from the multi-cyclone filter.

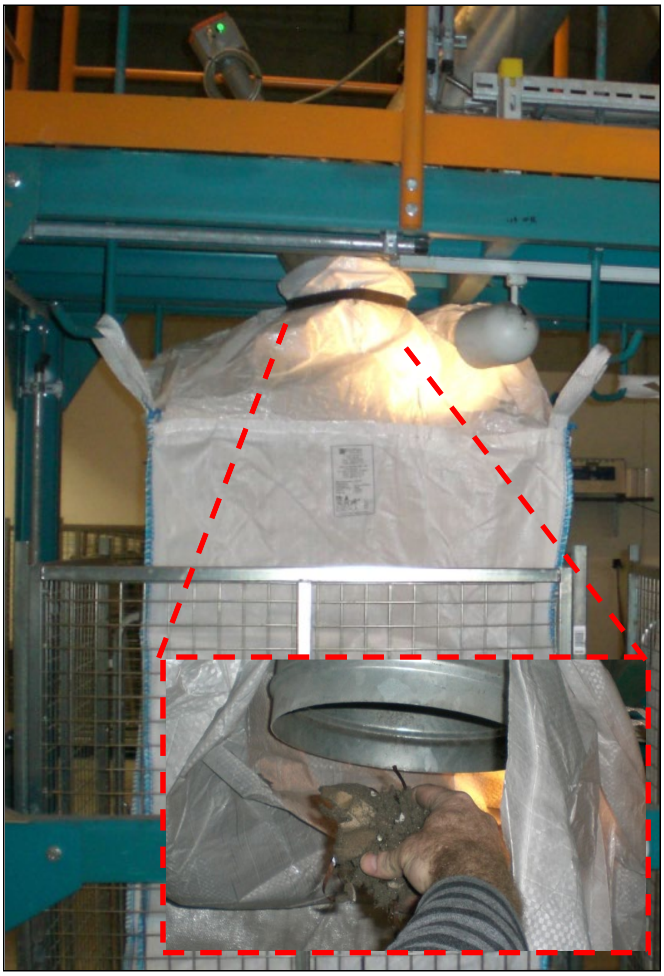

Figure 4 Output from the cyclone filter.

The third filter is a jet-filter taking out the last parts from the air. The generation is approx. 200-300 kg/year which is treated as hazardous waste and sent to Kommunekemi (www.kommunekemi.dk). Table 6 summarizes the filter residue production and fate.

Table 6 output from each filter and final treatment*

Filter	Output	Ca. kg	% of total WEEE input	Final treatment
Multi-Cyclone	Largest fraction	500 kg/month	0.037%	Incineration
Cyclone	Smaller fractions	400 kg/month	0.030%	Mainly incineration (some dust contains high value material, and is treated for recycling)
Jet	Finest fraction	200-300 kg/year	0.002%	Special treatment (hazardous waste)

*provided figures do not represent exact numbers.

The air passing through the jet-filter is ejected into the surrounding air outside. The filter is continuously controlled by a filter control system to make sure the filter is intact and effective. Filter specifications according to plant manager, Tom Ellergaard, is maximum 10 mg/cbm i.N.tr., measured according to DIN VDI 2066.

There is no knowledge on the potential presence of gaseous compounds to the outside air such as e.g. beryllium. The numbers in table 6 are used in the calculations presented in chapter 4.8.

4.5 Automatic sorting line

The smaller units (< 10x10 cm) are separated in the size sorting stage and enter the automatic sorting line. The automatic sorting line consists of a two part magnet setup and an eddy current separator. The magnet setup is able to separate a fraction mainly consisting of electromotor units and transformers – hence given the name ‘motor-trafo 1’ at the facility. Figure 5 below shows the fraction from the first magnet part. The second magnet part is removing a similar fraction but in smaller sizes, that is called ‘motor-trafo 2’. The eddy current separation unit separates the remaining, nonferrous metal from the residual fraction. The result is seen in Figure 6. The removed fraction has a high content of aluminium and is therefore almost ready to be sent to a metal smelter for recovery. The automatic separation line (the magnet setup and eddy current unit) takes place under indoor ‘atmospheric’ conditions. No air suction/cleaning is applied. Currently, the residual fraction from the automatic sorting line is sent to further treatment as fine mechanical/optical sorting, to improve the recyclability level. This fraction may in fact still contain valuable materials, like e.g. aluminium.

Figure 5 Fraction from over-belt magnet consisting mainly of electromotor and transformer waste (‘motor-trafo 1’).

Figure 6 Fraction separated by the eddy current separation unit.

4.6 Manual sorting

The large unit fraction (> 10 x 10 cm) from the size sorting enters the manual sorting line. The manual sorting line has space for eight workers. Each of them is sorting out one or two valuable fractions of material which is thrown down through ‘sorting holes’ into containers below. A list of materials posted on the wall prioritizes the different material fractions depending on material value in case the material flow is too large to handle. The list specifies units that have to be removed before and during the pre-sorting stage, like e.g. displays, and functions as a check list in case of missed sorting. These units must be manually removed and put together with the pre-sorted fractions. Also the residual fraction from the manual sorting still contains valuable materials. For this reason, it is considered to construct a new line to treat the residual fraction together with the residual fraction remaining from the automatic sorting line. An overview of the material fractions sorted in the manual and automatic sorting lines is given in Table 7.

Table 7 Sorted fractions from primary magnet, automatic, and manual sorting line at Averhoff*

Sorting line	Sorted fraction
Primary magnet	Iron
	Batteries missed during pre-sorting
	Return fraction (Returns to shredding)
Automatic line	Motor/trafo 1
	Motor/trafo 2
	Aluminium
	Residual fraction
Manual line	Printed wiring board, high quality
	Printed wiring board, low quality
	Cables, clean, high copper content
	Cables, un-clean, low copper content
	Aluminium
	Motor/trafo
	Mixed metals
	Garbage and wood
	Residual fraction
	Waste like paper, paperboard, foam rubber, textile and wood pieces.
	Plastics

*The list is not complete, but does contain the most important fractions. Data are reported respecting the privacy requirements expressed by the company.

In the manual sorting stage, the workers are wearing gloves but not breathing masks. The manual line is contained in a cabin provided with a fresh air system, to insure pre heated or cool air to the sorting crew. The cabin air is replaced several times per hour. A measuring of the air quality and dust content has been done to ensure the working environment. The result of this test is presented in Table 16. Depending on the quality of the sorted fraction, these are sold and exported for further reuse and recycling (e.g. PWB, high quality) while others end up at final disposal land filling and incineration at ordinary waste-to-energy plants or kommunekemi (cf. Chapter 4.8).

4.7 Storage of materials

During the day received material will be stored shortly outside before the cages are emptied and the material is pre-sorted. The photo below (Figure 7) shows an aerial view of the treatment plant where cages with electronic equipment are seen outside.

Figure 7 Aerial view of Averhoff treatment plant (www.averhoff.dk)

With storage outside, it is possible that substances can be released;

- During rain, as emission to wastewater
- During sunshine, as evaporation of chemical compounds

According to the local permission some material fractions are stored outside with the storage specifications reported in Table 8.

Table 8 Storage of sorted materials

Material fraction	Storage
Cables	Outside, under cover
Electromotor and transformer (motor-trafo)	Outside, not covered
Iron and aluminium	Outside, not covered
Combustible waste sent to incineration	Compressed

4.8 Resource recovery and recyclability

Both the materials sorted in the pre-shredding and post-shredding phase need to be further treated and processed in other facilities that can be of various types. A minor quantity of components is re-used directly, e.g. toner cartridges that are sent to Sweden. All the fractions that contain valuable metals (like e.g. Al, Cu, Fe) are sent to metal smelters outside Denmark, where the metals are extracted and recovered. Glass, batteries, and sorted plastic that is categorised as not containing hazardous substances (cf. Chapter 4.2) are sent to the respective recycling facilities, also located outside Denmark. The materials can then be recycled according to the efficiency of the facility. Fractions with a valuable calorific value and low content of hazardous substances (cf. Chapter 4.2) are sent to energy recovery in Danish municipal waste combustion plants (this is e.g. the case of some plastic, corresponding to approx. 1% of the total input), while minor quantities are deposited in landfill. Last, the fraction contaminated by hazardous substances is considered as hazardous waste and treated at the hazardous waste combustion plant Kommunekemi. The quantities are briefly shown in the mass balance of Figure 8, while Table 9 reports type and quantity of the materials that are sent to the various destinations.

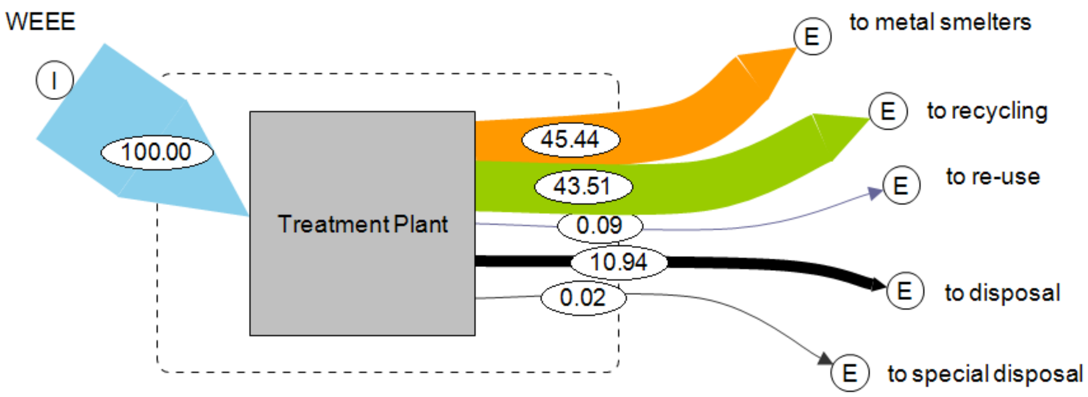

Figure 8 Principal quantities and destination for WEEE sorted at the Averhoff's recycling plant. Data are normalized to 100 t/a. I = import; E = Export.

Given the information about weight of total WEEE input to the facility (Cf. Chapter 4.1) and the percentage of total WEEE input for the different output flows (Figure 8 and table) as provided by Averhoff, it is possible to calculate the total weight of WEEE from which energy is recovered in a power plant, i.e. incinerated WEEE sub-fractions (defined as "D" in Chapter 3), and the total weight of residue WEEE which is disposed of to landfills (defined as "E" in Chapter 3). For this specific pre-processing facility, D equals approximately 1500 tons/year while E equals approximately 41.5 tons/year. These data can be used in subsequent substance flow analysis to calculate the hazardous and precious substance input from WEEE to incinerators and landfills; the latter given that the composition of the WEEE output flows from the shredder plant is known. Once the input to the incinerator/landfill is known, additional estimates of primary, secondary and tertiary emissions may be obtained, and from these, resulting dispersion and exposure, may eventually be obtained via appropriate modelling.

Table 9 Final treatment for sorted fractions for which information is available.

Materials/components in the output fraction	**% of total WEEE input**	**Final treatment**
Plastics parts from dismantling (HS below ROHS/REACH values); CRT tubes; Ni-Cd, NiMH, Li-containing, and mixed batteries; CFC/HCFC/HFC cooling and freezing appliances	43.51%	Recycling
Mix of flat panel displays; printed wiring boards without Br-FR; cables (mix); shredder iron fraction; mobiles, non-ferrous metal fraction	45.44%	Metal Smelter
Mix of toner and ink cartridges	0.09%	Re-use
Wood fractions and pieces from dismantling; Plastics parts from dismantling (HS above ROHS/REACH values); glass fractions from dismantling; CRT glass pieces; residual waste from dismantling; filter residue	10.94%	Disposal (Incineration /landfilling)
Electrolyte capacitors; mix of PCB-containing capacitors; mercury-containing components; filter residues; special displays and beryllium-containing units.	0.02%	Special Disposal

As arises clearly from the previous chapters and until this point, the existing and available data regarding material and substance flows within the Danish WEEE system are not sufficient for a detailed substance flow analysis to be performed. The main reasons are the non-transparent flow of different materials in the collection and pre-processing stages, and the generic nomenclature. Knowledge on content of hazardous compounds is also generic and mainly restricted to sub-fractions that are manually sorted prior to shredding according to the WEEE-directive.

Chapter 5 presents therefore existing knowledge from scientific literature regarding the content and concentration level of precious and hazardous compounds within selected WEEE fractions, while chapter 6 presents a SFA of hazardous compounds for which literature data are available regarding concentration in different WEEE sorted fractions.

5 Substance composition of WEEE

Items defined as WEEE have generally a complex composition and contain a mixture of substances. Further, WEEE appears to be highly heterogeneous, thus it is not straightforward to determine univocally the WEEE composition, which may be highly variable in time and space (Cui and Zhang, 2008).
Two categories of substances are particularly interesting in relation to sustainable WEEE management: hazardous and valuable (recoverable/precious).
The content of hazardous and valuable substances in WEEE has been analysed in previous studies (European Topic Centre on Waste, 2003; Widmer et al., 2005; Morf et al., 2007; Schlummer et al., 2007; Gross et al., 2008; Robinson, 2009; Chancerel et al., 2009). Two main approaches are usually applied: the WEEE composition is estimated a) based on the known composition of single WEEE components (e.g. Mercury in switches, Cadmium and Lead in batteries) and b) through WEEE sampling and analysis of the chemical composition.
A literature survey has been performed in this study in order to provide an overview of existing knowledge on hazardous and valuable compounds contained within the ten product categories from the WEEE directive (cf. Table 4).

5.1 Hazardous Substances (HS) in WEEE

Given the number of parts and materials that most electronics are made of, the majority of WEEE types is included in the List A of Annex VIII of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (Manhart, 2010) and are therefore classified as hazardous waste within this convention.
WEEE can contain organic, inorganic and even radio-active hazardous substances. The most hazardous WEEE components are: cathode ray tubes, printed wiring boards, batteries, gas discharge lamps, and plastics. A recent review by (Tsydenova and Bengtsson, 2011) reports a list of the hazardous substances that can be found inside each of these components. A summary of this and newest information represented by a comprehensive list of the hazardous substances that can be present in WEEE (Onwughara et al., 2010; Robinson, 2009; Tsydenova and Bengtsson, 2011) are reported in Table 10. The table shows the occurrence of each hazardous substance in different WEEE types.

Table 10 Hazardous substances in WEEE, the components containing each substance are listed.

Substance	Occurrence in WEEE	Concentration in WEEE (mg/kg)[a]
Halogenated compounds:		
- PCB (polychlorinated biphenyls)	Condensers, Transformers	13
- TBBP-A (tetrabromo-bisphenol-A)	Flame retardants for plastics (thermoplastic components, cable insulation)	1420

- PBB* (polybrominated biphenyls)	TBBA is presently the most widely used flame retardant in printed wiring boards (PWB) and casings.	
- PentaBDE (pentabromodiphenyl ether)*	Flame retardant in PWBs, connectors and plastic covers.	34
- Chlorofluorocarbon (CFC)	Cooling unit, Insulation foam	
- PVC (polyvinyl chloride)	Cable insulation	
Metals:		
- Diantimony trioxide	Contained in flame retardants in PWBs	
- Arsenic	Small quantities in the form of gallium arsenide within light emitting diodes	
- Barium	Getters in CRT	
- Beryllium	Power supply boxes which contain silicon controlled rectifiers and x-ray lenses	
- Cadmium*	Rechargeable NiCd-batteries, fluorescent layer (CRT screens), printer inks and toners, photocopying-machines (printer drums), accumulators	180
- Chromium VI*	Data tapes, floppy-disks	9900
- Gallium arsenide	LED light emitting Diode, solar cells (ECHA, 2010[b]), semiconductors (microchips) in wireless and Wi-Fi consumer electronic products (EECA, 2007)	
- Germanium	Photodiodes	
- Indium	LCD glass, semiconductors	
- Lead*	CRT screens, batteries, printed wiring boards, accumulators	2900
- Lithium	Li-batteries	
- Mercury*	Fluorescent lamps and vapour lamps. Fluorescent lamps that provide backlighting in LCDs. Some alkaline batteries. Mercury wetted switches, accumulators	0.68
- Nickel	Rechargeable NiCd-batteries or NiMH-batteries, electron gun in CRT, accumulators	10300
- Rare Earth elements (Yttrium, Europium)	Fluorescent layer (CRT-screen)	
- Ruthenium	Hard discs	
- Selenium	Older photocopying-machines (photo drums)	
- Zinc sulphide	Interior of CRT screens, mixed with rare earth metals	
Others:		
- Toner Dust	Toner cartridges for laser printers / copiers	
Radio-active substances:		
- Americium	Medical equipment, fire detectors, active sensing element in smoke detectors	

[a] Data from Morf et al. (2007)
[b] ECHA, 2010a, 2010b and 2010c
* Substances already under RoHS regulation

Literature data reporting elemental analyses and w/w per cent content of hazardous substances in WEEE are scarce. Quantitative data on the actual levels of metals, non-metals, PCB and Brominated Flame Retardants (BFR) in small WEEE and in the plastic fraction of small WEEE have been e.g. reported by (Morf et al., 2005; Morf et al., 2007) with reference to Swiss conditions.

A significant body of information exists regarding the composition of different EEE products, from mobile phones, to printed wiring boards or coffee machines, as reviewed by (Chancerel and Rotter, 2009). Due to the heterogeneity of EEE products, the w/w per cent content of hazardous substances in such items, even inside the same category of components (e.g. mobile phones), is highly variable.

The risks related to humans upon exposure from hazardous substances compounds in WEEE are discussed in Chapter 7.

5.1.1 Hazardous substances outside the regulation of the RoHS directive

The Directive 2002/95/EC on the Restriction of Hazardous Substances (RoHS) establishes that since July 2006 the following substances are restricted in new electrical and electronic equipment: lead, mercury, cadmium, hexavalent chromium and polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE), which are used as flame retardants in plastics.
There is a limitation of this directive: a number of EEE components are considered as exceptions and are not covered by the regulation (Wright, 2007). As a result, minor quantities of the regulated toxics will still be present during the treatment of WEEE.
In a recent report, Gross and co-workers (Gross et al., 2008) focus on the hazardous substances not regulated by the RoHS directive and select a number of substances of concern in addition to the ones already listed in the RoHS directive. The selection is made according to four criteria (Gross et al., 2008):

1. Substances meeting the criteria for classification as dangerous in accordance with the Dangerous Substances Directive (Directive 67/548/EEC), that applies to pure chemicals marketed in the EU;
2. Substances meeting the criteria for classification as substances of very high concern (SVHC) in accordance with REACH.
3. Substances which have been found as contaminants in humans and biota.
4. Substances which can form hazardous substances during the collecting and treatment of waste electrical and electronic equipment.

Main findings from the study are reported in Table 11. Gross and co-workers recommend the inclusion of five organic substances in RoHS. Regarding inorganic substances, labelling is suggested for Beryllium and its oxides, and for Indium Phosphide and Gallium Arsenide. Finally, PVC used in wires and cables and organochlorine and organobromine compounds used as flame retardants are substances of concern according to criteria 4 cited above due to the risk that can potentially occur during their end-of-life treatment (e.g. dioxins and furans may form in the combustion of brominated flame retardants and PVC in open fires or at low temperatures in improperly functioning incinerators).

Table 11 High priority hazardous substances according to Gross et al. Main use in EEE, marketed quantities and recommendation for inclusion in RoHS is reported.

Candidate substance	Main use in EEE	Total quantity used in EEE [t/y in EU]*	Recommendation
Tetrabromo bisphenol A (TBBP-A)	Reactive FR in epoxy and polycarbonate resin, Additive FR in ABS	40000	Inclusion in RoHS(Gross et al., 2008)
Hexabromo-cyclododecane (HBCDD)	Flame retardant in HIPS, e.g. in audio-visual equipment, wire, cables	210	Inclusion in RoHS(Gross et al., 2008)
Bis (2-ethylhexyl) phthalate (DEHP)	Plasticizer in PVC cables; Encapsulation/potting of electronic components	29000	Inclusion in RoHS(Gross et al., 2008)
Butylbenzyl-phthalate (BBP)	Plasticizer in PVC cables Encapsulation/potting of electronic components	Total use: 19500 (no data available on share of EEE applications)	Inclusion in RoHS(Gross et al., 2008)
Dibutylphthalate (DBP)	Plasticizer in PVC cables; Encapsulation/potting of electronics components Silber conductive paint for variable resistors	Total use: 14800 (no data available on share of EEE applications)	Inclusion in RoHS(Gross et al., 2008)
Beryllium metal	Beryllium metal and composites: Optical instruments, X-ray windows Beryllium-containing alloys: current carrying springs, integrated circuitry sockets, Silicon-controlled rectifiers (Robinson, 2009), Connectors in printed wiring boards (Tsydenova, 2010)	Be metal and composites: 2; Be- containing alloys: 11,5	Labelling for correct end-of-life treatment, classified as a carcinogen, class 2 (Gross et al., 2008)
Beryllium oxide (BeO)	BeO ceramic applications: Laser bores and tubes Power transistors, transistor and valve bases, some resistors (Defra, 2004)	15 n/n	Labelling for correct end-of-life treatment, classified as a carcinogen, Cat. 2 (Gross et al., 2008)
Indium Phosphide (InP)	Semiconductors	n/n	Labelling as carcinogen and toxic for reproduction (ECHA, 2010a and b)
Gallium Arsenide (GaAs)	LED, mobile handsets and Wi-Fi applications, opto-electronics, and control systems	n/n	Labelling as Carc. Cat. 1; R45; Repro. Cat. 2; R60; T; R48/23 (ECHA, 2010c)

*Values represent share of substance used in EEE, data are extrapolation of annual flows of various EEE products.

5.1.2 REACH compliance declarations web database

REACH introduces new requirements on EU component suppliers and equipment manufacturers with respect to Substances of Very High Concern

(SVHC) to provide substance declarations when they supply their articles (e.g. components and sub-assemblies) to the next manufacturer in the supply chain. REACH is fundamentally different to RoHS where there is no legal obligation on EU suppliers to provide information on the content of substances of their components and sub-assemblies.
Starting from October 2008 when the first Candidate List was published, Article 33 (1) of the REACH Regulation places a legal obligation on all EU suppliers to inform their manufacturing customers whether the components or assemblies they supply contain any of the REACH Candidate List substances in concentrations > 0.1% w/w. For all components or assemblies which exceed this concentration, the supplier has a legal obligation to provide information on safe use.
In order to reduce the compliance cost for the suppliers and manufactures the industry has created a location on the internet where both suppliers and manufactures can upload their substances declarations. Information is not public but can be purchased by members. The database provides information about the type and quantity of hazardous substances included in different categories of WEEE components, provided directly by product suppliers. The information provided merely as a support in the implementation of safe management practices, and is used in the industry (e.g. by Philips, Siemens and a wide range of OEMs - original equipment manufacturers, see http://www.environcorp.com) as well as in the WEEE management sector.

5.2 Valuable and precious substances in WEEE

The treatment of WEEE is in particular driven by the recovery of the valuable substances and materials. As seen before in Chapter 4, the most significant valuable metallic fractions that are easily recovered from WEEE are the magnetic and aluminium fractions, and the copper one. The first two are treated in steel and aluminium smelters respectively. The third fraction is treated in copper smelters and both copper and precious metals are than extracted from the copper-rich waste stream (Manhart, 2010). The recyclability rate of these fractions from WEEE is mostly high (Table 12).

Table 12 Recyclability of metals contained in a PC (modified from Env. Canada, 2004).

Recyclability	Metal
95-99%	Gold, palladium, silver, platinum
80-95%	Aluminium, iron, copper, nickel, ruthenium, cobalt
50-80%	Tin, zinc, selenium, rhodium
1-49%	Plastics, lead
0%	Germanium, gallium, barium, vanadium, terbium, beryllium, europium, titanium, manganese, antimony, bismuth, chromium, cadmium, niobium, yttrium, mercury, arsenic

Beside the main recyclable and valuable metal fractions, both precious metals (Gold, Silver, and metals of the Platinum-group) and special metals (Selenium, Tellurium, Bismuth, Antimony, and Indium) can be found in WEEE. Precious and special metals are usually included in complex WEEE components, in small concentrations per unit, like in the case of printed wiring boards (Chancerel et al., 2009; Onwughara et al, 2010). The content of Gold, Silver and Palladium in printed wiring boards of various WEEE components has been determined by Chancerel and co-workers (Chancerel et al., 2009) and is reported in Table 13.

Table 13 Mass of precious metals in various components of WEEE that constitute an input to a WEEE sorting facility.

	Mass of metals in the input fraction (g / ton)*		
Equipment type	Ag	Au	Pd
Computer keyboard	14	1.4	0.6
LCD monitor	52	19.6	3.96
Computer mouse	56	5.6	2.4
DVD player	70	10	2.1
Hi-. unit	53.92	2.48	0.8
Laptop	150	37.5	16.5
Loudspeaker	13.48	0.62	0.2
Mobile telephone	1218.8	215.6	62.7
Personal computer	130	32.5	14.3
Printer, fax	28	3.76	0.72
Radio set	104	13.6	1.6
Telephone	493.68	11	53.02
Video recorder	67.4	3.1	1
Others	46.8	6.12	0.72
Total input WEEE	67.6	11.2	4.4

*Estimates of precious metals are based on the content of printed wiring boards in the different WEEE equipment types. This could be an underestimation of the actual total content of the metals in WEEE. Data have been calculated from values reported in (Chancerel et al., 2009)

The concentration of non-ferrous metals and precious metals in WEEE items has been gradually decreasing during time due to technological improvements in the manufacturing of electronics (Cui and Zhang, 2008). However, Chancerel (2009) states that the content of precious metals in WEEE components like e.g. PWBs is still higher than the content in metals ore. Furthermore, the amount of WEEE produced annually keeps increasing, so that such substances are, and will be in the future, contained in WEEE in significant amounts.

Despite their high recyclability (Table 12), the extraction rate for precious metals from WEEE is low, and significant amount are attached to fractions from which they are not recovered (Manhart, 2010). Limits of, and barriers towards, an increased recovery of such substances are described in chapter 8.

6 Substance flow analysis for selected hazardous substances in a Danish pre-processing facility

The analysis of the flows (mass over time) of hazardous substances in the WEEE management system is the first step in the quantification of the primary emission related to such practice. This analysis allows focusing on the amount of substances that are transferred between consecutive steps and processes in the waste management chain, and allows focusing on the amount of hazardous compounds transferred from the waste to the environment during the treatment (primary emissions).

In this chapter the flow of some hazardous substances thorough a Danish WEEE sorting facility is estimated based on 1) data on concentration of hazardous substances in WEEE from literature and on 2) WEEE flows data from the facility itself.

The objective is to provide an absolute estimate of the amounts of hazardous substances in specific output fractions. This information is of particular relevance when the final destination and treatment of each output flow from the facility is considered. In fact, it constitutes e.g. an estimate of the "contamination" of fractions that are going to be recycled or that are disposed via thermal treatment. This allows qualitative considerations about the potential impacts related to the secondary and tertiary emissions occurring during the treatment of the output fractions.

6.1 Selection of substances

Initially, the scope of the report was to provide a substance flow analysis for a number of hazardous substances not included in the RoHS directive. However, the lack of quantitative data constituted an obstacle to the fulfilling of such scope. Based on the data available, a flow analysis is here presented regarding the substances included in RoHS (Pb, Cd, Cr, Hg; pentaBDE). This analysis is based on data collected before 2006, when the RoHS directive was not yet implemented, and is likely to overestimate actual flows of hazardous substances in the Danish WEEE system. However, this is the first attempt to quantify flows of hazardous substances in the Danish WEEE management system, and it is here used to illustrate the principles behind the SFA calculations. Furthermore, SFA is performed for three of the compounds specified in chapter 5.1.1, that are not included in the directive, specifically TBBP-A (Tetrabromo-bisphenol-A), HBCDD (Hexabromo-cyclododecane), and Beryllium. Differently from the first two compounds, no specific data were available for Beryllium; a qualitative analysis is therefore presented where proxy estimates are discussed.

6.2 Aggregation of output flows

The analysis here presented is a substance flow analysis for the WEEE pre-processing facility presented in Chapter 4. Data regarding the amounts of WEEE treated in 2010 in the facility, and of the resulting amounts of different output fractions have been used.
Literature data regarding the concentration of hazardous substances in different output fractions from WEEE pre-processing have been used (Morf and Taverna (2004), Morf et al. (2005), Morf et al. (2007). In their study, Morf and co-workers determined by chemical analysis the content of hazardous substances both in input WEEE and in the output fractions from a pre-processing facility in Switzerland. The facility analysed treats approximately 13000 tons of small WEEE appliances ranging from small to large size. These correspond to the Danish WEEE category no. 2, no. 3 and no. 4 (see Chapter 2.2.1.). The Swiss facility can be comparable to the Danish Averhoff facility both in terms of size and type of material treated. The concentration [mg/kg] of Pb, Cd, Cr, Hg, PentaBDE, TBBP-A, HBCDD in specific output fractions can be calculated from data reported in Morf et al. (2004) (Table 15). Output data from Averhoff were aggregated in order to fit qualitatively the output categories individuated by Morf, as it can be seen from table 14. No specific chemical analysis has been performed in this project.
Table 14 shows the differences between the output flows of the Swiss and he Danish facility. First, the amount of different output fractions in terms of % input is slightly different between the facilities. This may depend on different efficiencies in the treatment phase. However, relative proportions between output fractions are consistent: plastic (intended as total plastic: the sum of PC/TV castings and the grained fractions) and metal scrap fraction (intended as total metals scrap: the sum of the grained fractions, metal scrap and Fe scrap) are comparable in magnitude, whereas cables, filter residues and batteries are one order of magnitude lower in both cases. Second, the Danish facility doesn't shred the material into pieces of size minor than 10 x 10 cm, so the fine grained fractions are missing. These differences between the two facilities increase the uncertainties in assuming that the concentration of hazardous substances in the Danish output fractions is the same as the concentration in the Swiss fractions. These fractions may in fact be not identical in terms of composition. However, it is used as the best approximation considered the information available. In the following calculation the composition of the output fraction in terms of hazardous substances is assumed to be the same in the two facilities.

Table 14 Output fraction form a Swiss WEEE processing facility and correspondent aggregated output fractions from the Danish facility. The classes are compared both in qualitative terms (type of material and final destination) and quantitative terms (% of total input). PCB = Polychlorobiphenyl; PWB = Printed circuit (Wired) Boards; CRT = cathode ray tubes; Nn = missing.

Output Fraction		% of total input		Destination	
Morf et al. (2004)	Averhoff, 2010 (aggregated)	Morf et al. (2004)	Averhoff (2010)	Morf et al. (2004)	Averhoff (2010)
Pollutant carrier (batteries/capacitors)	mix of PCB containing capacitors; mercury components; electrolyte capacitors; Ni-Cd batteries; NiMH batteries; Li-containing batteries ; mix of all batteries	1%	0.18%	[Batteries Recycling]	[Batteries Recycling]
Fine particulates	Filter residues	7%	0.07%	[Metal recycling]	[Special disposal]
Cu cables	Cables (mix)	2%	6.57%	[Metal recycling]	[Metal recycling]
Printed wiring boards (PWB)	Mix of PWB from dismantling; mobiles ; PWB and power supply units	2%	14.95%	[Metal recycling]	[Metal recycling]
Cathode ray tube components	CRT 'tubes' from dismantling	20%	29.15%	[Recycling]	[Recycling]
Plastics and wooden castings (PC/TV)	plastics 'parts' from dismantling; wood fractions from dismantling (mix); "pure" wood pieces; metal/plastics mixtures	3%	25.00%	[Waste incineration]	[Recycling and thermal treatment]
Fine grained plastics fractions (<10mm)	Nn	20%	Nn	[Waste incineration]	Nn
Fine grained metal fractions (<10mm)	Nn	7%	Nn	[Metal recycling]	Nn
Metal scrap fractions	Other 'metal fractions' from dismantling; deflection units; mix of flat panel displays; electric motors/dry transformers (mix)	7%	8.19%	[Metal recycling]	[Metal recycling]
Fe scrap fractions	shredder iron fraction	31%	15.89%	[Metal recycling]	[Metal recycling]

Table 15a Concentration of hazardous substances (not included in the WEEE directive) in different WEEE sorting output fractions from a Swiss facility*.

[mg/kg]	Be	HBCDD	TBBP-A
Pollutant carrier (batteries/capacitors)	0.00	0.00	0.00
Fine particulates	0.10	10.00	625.00
Cu cables	0.00	25.13	5.13
Printed circuit boards	100.00	10.53	42.11
Cathode ray tube components	0.00	0.00	0.00
Plastics and wooden castings (PC/TV)	0.00	174.60	18095.24
Metal scrap fractions 1-4	0.10	0.00	0.00
Fe scrap fractions	0.10	0.00	0.00

Table 16b Concentration of hazardous substances (included in the WEEE directive) in different WEEE sorting output fractions from a Swiss facility.

[mg/kg]	PentaBDE	Hg	Ni	Cr	Cd	Pb
Pollutant carrier (batteries/capacitors)	0.00	69.23	16153.85	2000.00	16153.85	12307.69
Fine particulates	50.00	1.75	2250.00	750.00	337.50	5875.00
Cu cables	25.13	0.00	0.00	0.00	2.56	15.38
Printed circuit boards	15.79	1.66	10526.32	1131.58	500.00	11842.11
Cathode ray tube components	0.00	0.00	1.56	0.00	0.00	4444.44
Plastics and wooden castings (PC/TV)	44.44	0.94	152.38	109.52	58.73	174.60
Metal scrap fractions 1-4	0.00	0.00	100000.00	100000.00	0.00	0.00
Fe scrap fractions	0.00	0.00	6338.03	6338.03	0.00	0.00

*All concentration values are calculated from data reported in Morf et al. (2004), except for data on beryllium (cfr. Chapter 6.5)

Concentration values presented in Table 15a and b originated from a study performed prior to the enforcement of the WEEE directive, which makes the estimates accordingly overestimated. If we assumed that the emissions from waste-to-energy combustions plants is an indicator of the metal content in WEEE, i.e. unintentional combustion of WEEE, a decrease in the metal content from 2006-2009 would be around 15-16% for Ni and Cr. However, an increase of 3-7% is observed for Hg, Cd and Pb (Nielsen et al. 2011), so if waste combustion represents unintentional WEEE combustion, this would indicate that the lifetime of EEE makes the impact of the WEEE directive not yet measureable.

6.3 Substance flows: Pb, Cd, Cr, Hg, pentaBDE, TBBP-A, HBCDD

Once the quantity Q [kg] of each output fraction i is known (Table 14), the mass M [mg] of each hazardous substance s that is leaving the facility within the output flow can be calculated if the concentration C [kg] of each hazardous substance in each output fraction is known (Table 15), according to the simple mass balance (1):

$$M_{is} = Q_i * C_{is} \quad (1)$$

The substance flows for Pb, Cd, Cr, Hg, pentaBDE, TBBP-A, HBCDD are reported in figure 9 to 15. It should be noted that by summing the output values, the total mass of contaminant in input is also estimated by the software. In fact, the "input = output" mass balance is respected (no losses of mass are assumed). Thus, an indication of the amount of substance entering in a year in the facility is provided. The software used for the substance flows calculation is STAN®, developed at the Vienna University of Technology (http://www.iwa.tuwien.ac.at).

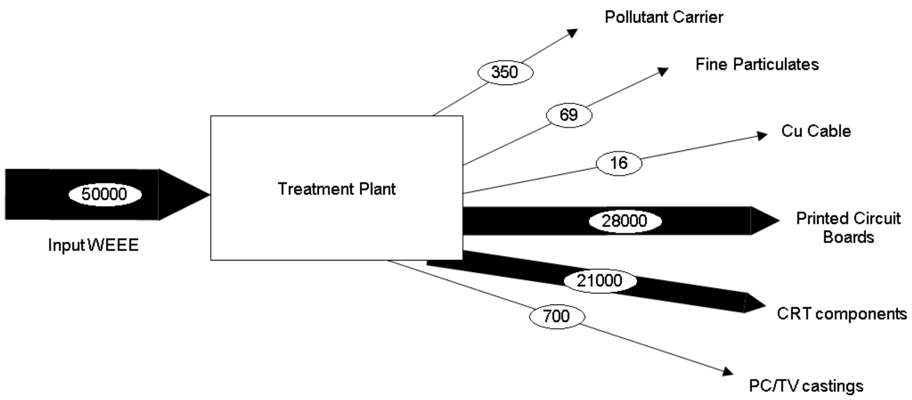

Figure 9 Substance Flow Analysis for lead (Pb) in a Danish WEEE pre-processing facility. Flow units are in [kg substance/year]

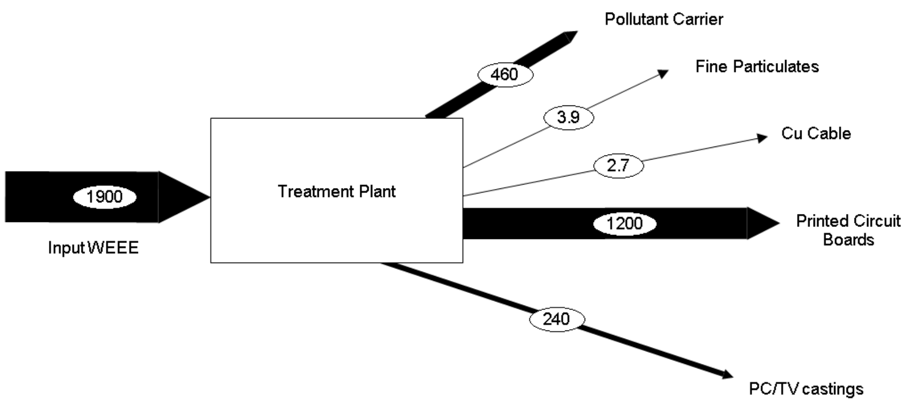

Figure 10 Substance Flow Analysis for cadmium (Cd) in a Danish WEEE pre-processing facility. Flow units are in [kg substance/year]

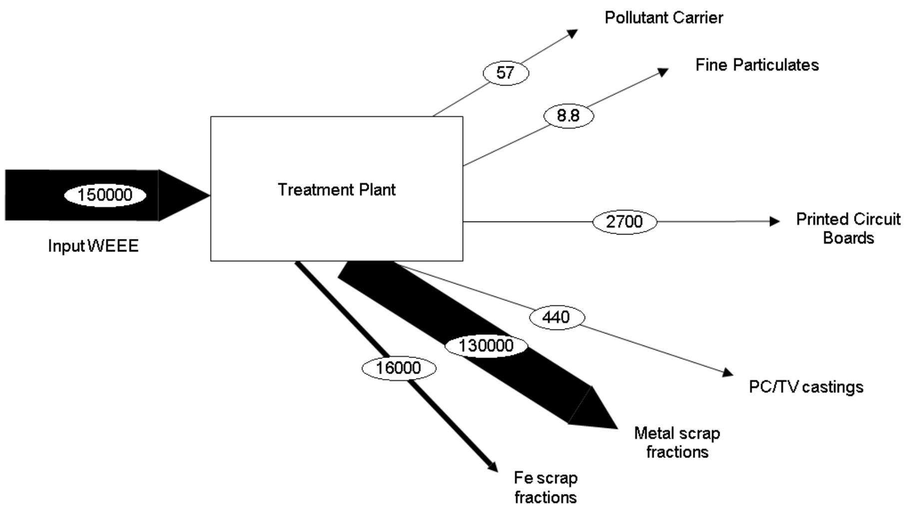

Figure 11 Substance Flow Analysis for chromium (Cr) in a Danish WEEE pre-processing facility. Flow units are in [kg substance/year]

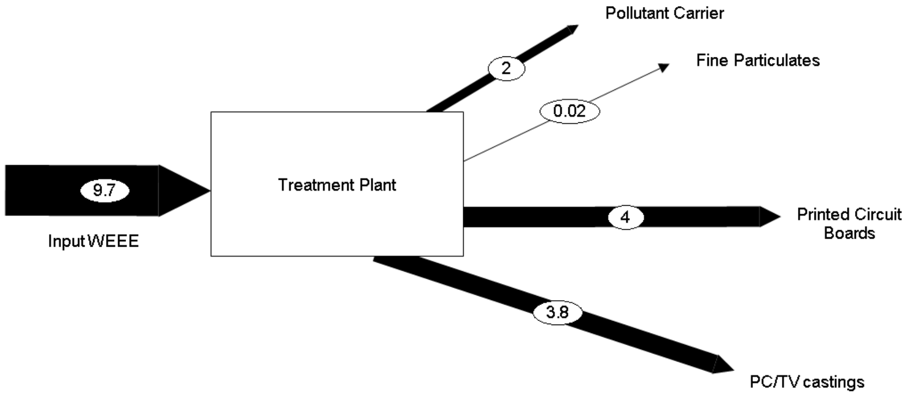

Figure 12 Substance Flow Analysis for mercury (Hg) in a Danish WEEE pre-processing facility. Flow units are in [kg substance/year]

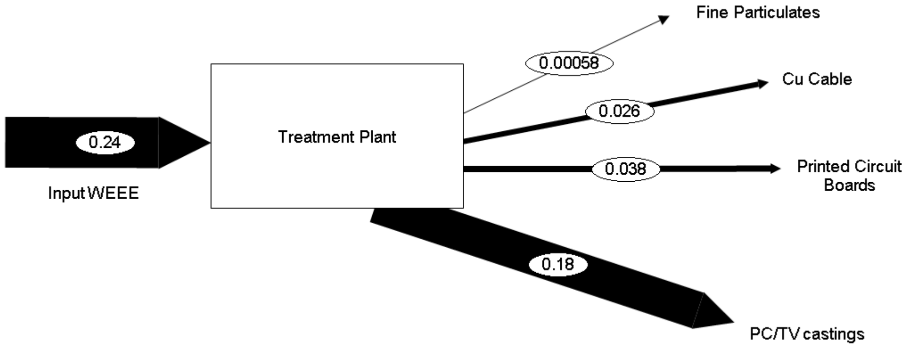

Figure 13 Substance Flow Analysis for Pentabromodiphenyl ether (pentaBDE) in a Danish WEEE pre-processing facility. Flow units are in [kg substance/year]

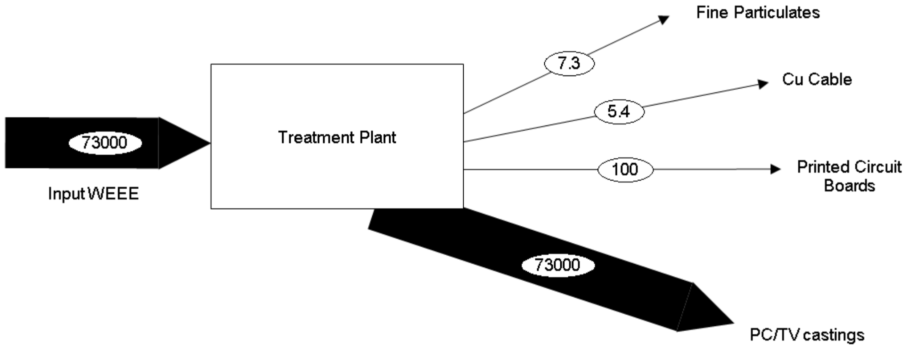

Figure 14 Substance Flow Analysis for Tetrabromo-bisphenol-A (TBBP-A) in a Danish WEEE pre-processing facility. Flow units are in [kg substance/year]

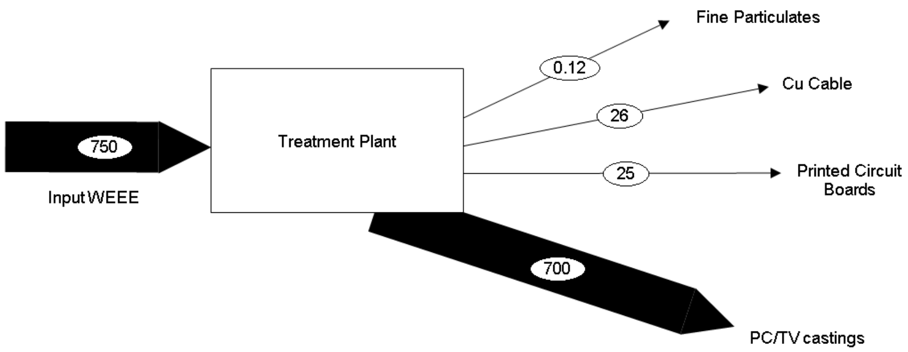

Figure 15 Substance Flow Analysis for Hexabromo-cyclododecane (HBCDD) in a Danish WEEE pre-processing facility. Flow units are in [kg substance/year]

The substance flow analysis here presented can be extended to other hazardous substances by keeping the same calculation principles. The limitation is the lack of quantitative data on hazardous substances concentration either in input WEEE or in output WEEE fractions. As soon as such data become available, e.g. via sampling or chemical analysis of specific WEEE output fractions or reporting of concentration of the content of specific compounds by the industry them self, a substance flow analysis for such compounds could be performed.

6.4 Discussion of substance flow analysis results

It must be remembered that data from Morf et al. for the substances already included in RoHS (Pb, Cd, Cr, Hg, pentaBDE) were collected before 2006, when the RoHS directive was not yet implemented. Therefore, a significant decrease in the concentration of such substances in WEEE (and consequently in the sorted WEEE output fractions) is expected in the future. The results are then likely to overestimate the reality and the actual flows of such hazardous substances in the Danish facility. Regarding metals, taking the Danish waste-to-energy plants as an indicator for the reduction in the metal content of WEEE, such overestimation could be up to around 16% (cf. chapter 6.2).

Keeping this in mind, it can be noted that:

1) As expected, printed wiring board are a carrier for metal pollutants, in particular lead, cadmium and chromium, and only in minor part mercury. It appears then very important manually to separate this fraction from the input WEEE with a high efficiency. Printed wiring boards or part of them from shredding ending up to disposal may be problematic because of the metal contaminations. This result shows also that, despite the lower concentration of metals in printed wiring boards compared to e.g. batteries, the flow of printed wiring boards is much higher in terms of quantity, thus leading to a more intense flow of metals in absolute terms. Manual sorting seems to be the most effective and environmental sustainable solution while shredding may result in downsized PWB content of various final disposal categories.
2) Large amounts of the toxic organic compounds are present in the plastic fraction (named as PC/TV castings in the figures) because of the high quantities of material involved (around 4000 tons/year) and because of the high concentration (around 18000 mg/kg and 174 mg/kg for TBBP-A and HBCDD respectively, according to Morf et al. (2004)). This may cause problems in the case of thermal treatment of such material, as discussed in the Chapter 7. It should be noted

how the flow of TBBP-A in plastic is much more significant than the flow in printed wiring boards, even if the BFR is intensively used in such component. High and low quality plastic fractions are reported, but no documentation for such categories presented or required.

3) The plastic fraction is also containing a significant amount of metals, which may be an obstacle for thermal treatment or recycling.

Considered the mass conservation principle, it is possible to use the data of mass of each output flow and relative concentration of hazardous substances to estimate the concentration of hazardous substances in the input WEEE entering the facility. In fact, the total mass of contaminant in input to the facility must equal the total mass of contaminant in output; any difference reflecting losses, e.g. emissions, during the shredding process. The result of such calculation is reported on following (Table 16), and is compared to the values previously measured and calculated by Morf (2007). The values show a good accordance, meaning that the aggregation of different Danish WEEE output fractions was successful in reflecting the classes proposed in the Swiss study. An exception to this is the concentration of TBBP-A and HBCDD that are overestimated (Table 16).

Table 17 Comparison of values of concentration [mg/kg] in input WEEE between the Danish and Swiss facility, for selected substances.

Substance	Concentration in input WEEE [mg/kg]		
	Measured (Morf, 2004)	Calculated via SFA (Morf, 2004)	Calculated via SFA (Present study)
Pb	2900	2869.57	3136.73
Cd	180	182.61	118.46
Cr	9900	10000.00	9399.09
Hg	0.68	0.70	0.61
PentaBDE	34	34.35	15.16
TBBPA	1420	1434.78	4531.15
HBCD	17	16.96	46.88

The uncertainty on the calculated values has not been estimated. Uncertainties may be both intrinsic, i.e. related to the modelling choices, and may be due to the calculation (error propagation). In the first case, the main contributor to uncertainty is the assumption that the composition of the output fractions from the Swiss and the Danish shredder plant is the same (Table 15). This is easier to assume for some fractions like Cu-cables than for other fractions like e.g. plastics from TV/PC, that are more heterogeneous regarding type and content of additives. Uncertainties in the assessment here presented are then expected to be higher for the plastic fraction. In fact, the composition of Cu cables is quite constant, being mostly Cu, while the composition of the plastic is not, so the uncertainty is higher in transferring the concentration value for hazardous substances in this sorted fraction from the Swiss case to the Danish one. In fact, as can be seen for table 16, the disagreement between literature and calculated values is higher for the substances PentaBDE, TBBPA and HBCD mainly found in plastic. In particular, the absolute input flows of TBBP-A and HBCDDs value are likely to be highly overestimated, while pentaBDE covers only a minor fraction of the total PBDE present in small WEEE; <5% of the octaBDE and decaBDE respectively. This because of uncertainties in the matching of plastic flows between the Swiss and Danish facility (cf. table 17). The uncertainty is estimated as of 1-2 two orders of magnitude. Morf and co-workers (2004) report 330 kg of TBBP-A as absolute input to the facility whereas the present study estimates 7300 kg, the difference is therefore large.

It should be also noted that there are some treatment differences between the Swiss and the Danish case. In particular, the material is not shredded in fine particles (<10 x 10 mm) in the Danish case. The concentration of contaminants may be higher in fine-grained particles due to difficulties in the sorting process, so that different materials are incidentally contaminated by undesired materials like e.g. plastic with printed wiring boards (Chancerel et al., 2009).
Regarding the calculation and related uncertainty, the use of standard deviations and confidence intervals in relation to the values of concentration may give a quantitative indication of how high are the uncertainties due to the measurements/calculation. Due to the limited data availability in this study it is not considered relevant to perform an uncertainty analysis.

Last, it is necessary to point out that while the data refer to absolute amounts in terms of mass, there is no specification about the form or speciation of the metals in the WEEE. These could be bounded strongly to other metals in alloys (e.g. chromium in stainless steel) and so being quite non-reactive. This adds another layer of uncertainty to be accounted for in any future assessment of emissions as input for risk assessment.

6.5 Estimates of beryllium flows

As mentioned in Chapter 5.1.1, Beryllium is a hazardous substance that is not included in the RoHS directive, but that is of concern. No detailed data were found regarding concentration of Beryllium in the output fractions, as in the case of the other substances. A tentative estimate of the Beryllium flows is however reported here based on other literature data and based on some assumptions presented in the following text. Beryllium can be found in mobile phones and PCs. In particular, UNEP estimates the concentration of beryllium in a mobile phone as less than 0.1% (1000 ppm) in weight, while Gross et al. (2008) provide a much lower value of 40 ppm. Regarding PCs, Environment Canada (2004) reports the concentration of Beryllium in a 27 kg-weight desktop PC to 157 ppm. These data are indicative; however they can be used as a proxy in estimating roughly the flows of Beryllium through the facility. Based on an average between the indicative values of 40 ppm and 157 ppm it is assumed that Beryllium is present in the printed wiring boards of PCs and mobile phones, in a concentration of 100 ± 80 ppm. Beryllium is not present in any other WEEE fraction according to the knowledge of the authors. Some shredded pieces of printed wiring board end up in the ferrous and nonferrous metal fraction, and in the filter residues, due to inefficiency in the sorting. An indicative value of 0.1 % of impurities made of printed wiring boards in these fractions is assumed. This is considered a worse-case scenario (high inefficiency in the sorting process). Using these data, an annual flow of 240 ± 190 kg Beryllium is estimated, and a concentration of 15 ± 12 mg/kg (ppm) of Beryllium in input WEEE (Figure 16).

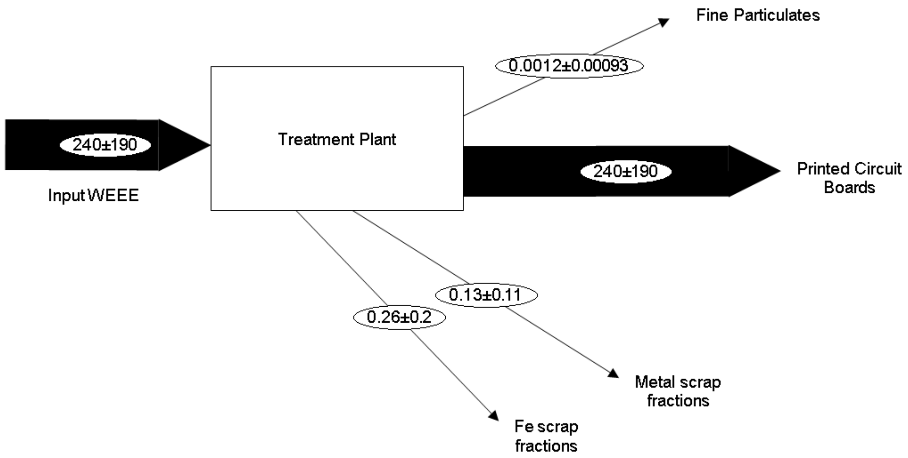

Figure 16 Substance Flow Analysis for Beryllium (Be) in a Danish WEEE pre-processing facility. Flow units are in [kg substance/year]

This may be an overestimation considered that the world production of Beryllium is around 200 tonnes yearly (OECD, 2010); however, even if uncertainties in the estimate are quite high, it can be at least considered as an upper limit value for content of beryllium in small WEEE.

Unfortunately, it has not been possible to perform similar screening estimates of the substance flow for other identified hazardous compounds of concern; i.e. Indium Phosphide, Gallium Arsenide, Americium, Germanium, Antimony trioxide, Brominated Flame Retardants (see Chapter 7.4).

6.6 Estimate of national flows via up-scaling

The Averhoff facility treats approximately 70% of the national collected WEEE belonging to the WEEE categories 2, 3 and 4. The results of the SFA for the facility can therefore be up-scaled to provide insights regarding the magnitude of the presence of the selected contaminants in the Danish WEEE management system. Results of the up-scaling are reported in Table 17 for the contaminants not included in RoHS.

Table 18 Substance Flow Analysis for Tetrabromo-bisphenol-A (TBBP-A), cyclododecane (HBCDD) and Beryllium (Be) in the Danish WEEE Management System (limited to the aggregate of WEEE categories 2, 3, and 4). Flow units are in [kg substance/year]

Substance [kg/y]	TBBP-A	HBCDD	Be
Input WEEE (Cat 2, 3, and 4 aggregated)	103936	1075	343
Pollutant Carrier	0	0	0
Fine Particulates	10	0.17	0.002
Cu Cable	8	38	0
Printed Circuit Boards	144	36	343
CRT components	0	0	0
PC/TV castings	103773	1001	0
Metal scrap fractions	0	0	0.19
Fe scrap fractions	0	0	0.36

This estimate here presented is limited to the WEEE categories 2, 3 and 4 considered in aggregate. The up-scaling can't therefore be assumed as representative for total generic WEEE in Denmark or for any of the Danish WEEE categories considered singularly. However, categories 2, 3 and 4 are the ones of biggest concern regarding the content of hazardous substances, the heterogeneity in terms of composition, and regarding the expected future increment in growth.

7 Potential environmental and human health Impacts

7.1 Relevant processes in the Danish context

A number of recent publications reviewed the existing knowledge regarding the potential environmental and human health impacts of e-waste recycling (Robinson, 2009; Frazzoli et al., 2010; Sepulveda et al., 2010; Tsydenova and Bengtsson, 2011). These studies provide, however, mainly qualitative information regarding potential impacts, or quantitative information limited to amounts of HS emitted from disposal of WEEE sorted fractions in pilot or actual facilities. The information or evidence of impacts linked to WEEE treatment in developed countries remains extremely scarce, while the literature on crude-recycling activities in developing countries appears to be more exhaustive.

In this chapter, the information that can be relevant for the Danish context is summarized. Treatment of WEEE in Denmark is limited to collection, dismantling and mechanical treatment oriented towards sorting. As mentioned in the previous chapters, after sorting the residual fractions are disposed via incineration or landfilling in Danish facilities while the valuable and recyclable fractions are sold and treated outside the country. Recycling facilities and smelters may produce significant emissions in terms of both greenhouse gases and toxic substances. These treatment processes have therefore a potential for impacts on humans and environment, both in the global and local scale, depending on the type and quantity of emission generated (e.g. mercury that is a global contaminant). However, the impacts related to recycling facilities (e.g. for batteries, plastics, etc.) and smelters are not considered in the present report, since the scope is limited to treatment within Denmark. Potential impacts on humans and on environment due to the treatment of WEEE in Danish facilities are here described qualitatively.

Two processes belonging to the Danish WEEE life cycle system can be considered as most relevant in terms of emissions and impacts (Figure 9):

1) pre-processing facilities: during the dismantling and shredding of the WEEE waste, workers may be exposed to hazardous substances. Occupational exposure is here the focus.
2) disposal in Danish thermal treatment plants or landfills of non-recyclable fractions from WEEE sorting and of fractions containing hazardous substances. The general population may be exposed to the emission, from the facility, of hazardous substances previously contained in the WEEE or to secondary emissions due to the WEEE treatment. Human health and environmental impact is here the focus.

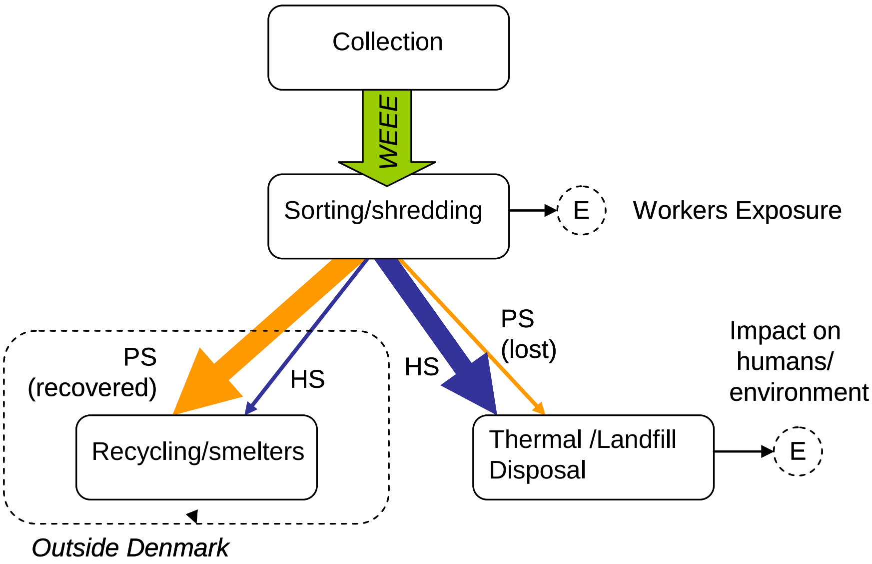

Figure 17 Simplified scheme of the WEEE flow in Denmark. Specific substance flows are highlighted, that are relevant in terms of resource conservation and in terms of environmental impacts. PS - precious substances; HS - hazardous substances, E – emission into the environment.

7.2 Emission from pre-processing

The information regarding emissions related to pre-processing activities (i.e. sorting/dismantling/mechanical separation via shredding) is in general scarce, and no data with specific reference to Danish conditions can be found. Furthermore, data about measurement of emissions from WEEE pre-processing facilities are missing in the existing literature. In two recent LCA studies on the Swiss WEEE management system (Hischier et al., 2005; Wager et al., 2011), Wager and co-workers evaluate the environmental emissions occurring during the pre-processing stage as marginal (manual dismantling is considered as non-significant) compared to the ones of the end-processing stage (recycling/smelting facilities).

Emissions into the external environment due to pre-processing may be due to:

- Dust produced by shredding activities that is not filtered. This is going to deposit in the soil surrounding the facility, where it can be ingested by organisms in the environment or by humans via the environment. Dust can contain absorbed hazardous substances. Such emissions can be effectively limited by filtering systems applied to the shredders.
- Drainage water containing minor amounts of hazardous substances leached from equipment and materials stored outdoor. Evaporation could also be a cause of emission in this case. Indoor storage of materials or use of covers is an effective way to avoid emissions. Furthermore, as in the case of the Averhoff facility (see chapter 4), there is no process water in use at the facility and the drainage water enters the municipal sewer and wastewater treatment.

At the present time, no information regarding measurement of contaminant concentration in the emitted dust and in soil and water in the vicinity of WEEE pre-processing facilities was found by the authors. This constitutes a crucial limitation to any impact assessment effort. The use of literature data (e.g. from LCA database) regarding emissions from generic shredding processes can be only poorly representative of WEEE processing, due to the peculiar composition and content in hazardous substances of WEEE compared to other kind of waste materials like e.g. automobile waste etc.. There is no overview of the storage of WEEE at the municipal collection stations before collection by the recycling companies. It is often seen that cages containing small/medium sized equipment, e.g. up to the sizes of PCs and computer screens, is stored under roof, and larger equipment, e.g. white goods, are stored outside (DPA-System, 2010a). However, all waste is stored outside, which is not in accordance to the WEEE directive.

7.3 Workers exposure

Improper handling of WEEE waste can result in exposure and bioaccumulation of hazardous substances and thus adverse health effects for the workers. This has been widely studied and demonstrated under the extreme conditions of Chinese workers in WEEE recycling sites (Frazzoli et al., 2010; Sepulveda et al., 2010). Despite that WEEE is considered as hazardous waste in List A of Annex VIII of the Basel Convention (on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal), and even if it is well documented that many different hazardous substances are present in WEEE, occupational studies regarding exposure of workers in WEEE pre-processing facilities are fragmented and scarce.
According Environment Canada (2004), the primary hazards related to WEEE pre-processing can be summarized according to each treatment step:

- Receiving area and classification of equipment: hazards in this stage are related to failure in recognizing immediately equipment or component containing hazardous substances. Accidental exposure may therefore take place via dermal contact with, or inhalation of hazardous substances from WEEE or in the dust. This phase is also crucial in determining the destination of each equipment type: inappropriate decision regarding destination may lead to inappropriate treatment and consequent potential exposure to hazardous substances.

- Manual disassembly: in this stage workers are in contact for a long time with the equipment. Thus there is the greatest potential for long-term exposure to hazardous substances. This may occur via inhalation of dust and hazardous substances emitted from the breakage of equipment and components, and via dermal contact when cutting, breaking, handling the material.

- Shredding: the mechanical treatment of the WEEE produces dust and airborne shredded parts of various sizes. Workers are exposed to the hazardous substances adsorbed to the particles primarily via inhalation, but eventually also via dermal contact during the subsequent manual sorting process.

In summary, the main routes of exposure to hazardous substances from WEEE are inhalation of dust and dermal contact, where the most significant pathway is inhalation of dust from shredding (in absence of proper or efficient filtering system) (Environment Canada, 2004). It should be noted that exposure via dermal contact may be more significant for inexperienced workers and this exposure pathway shouldn't be under estimated for this workers category.

Monitoring data in the working environment at the Averhoff facility is presented in Table 18.

Table 19 Lead concentration measured in air, dust and workers' blood at Averhoff facility (Averhoff, 2010, unpublished data).

	Pb_air [mg/m^3]	Dust [mg/m^3]	Pb_blood [µg/dl]
Number of samples	3	4	12
Average	0,003	0,475	7,350
Spread	0,001	0,190	4,425
Limit	0,05	10,00	20,00

The air concentration measurements are below the regulatory limit. They are around 2-3 orders of magnitude above measured concentrations for traffic (0.0079 µg/m3) and urban background levels (0.0039 µg/m3) in the city of Copenhagen (Pizzol et al., 2010a).

Biomonitoring data show a higher spread in the measured lead concentrations in blood (+/- 4,425 µg/dL) compared to the measured lead concentrations in air (+/- 0,001 mg/m^3), that may indicate differences in physiological parameters (Pizzol et al., 2010b) as well as variations hand to body contact related exposures.

7.4 Potential exposure to hazardous substances

Beryllium compounds

Regarding the substances of concern, the same report by Environment Canada states that: "workers may be exposed to levels of Beryllium, Cadmium and Lead which may result in adverse human health effects" (Environment Canada, 2004). This is the result of a preliminary quantitative exposure assessment that takes in account a) the toxicity of the mentioned substances b) the significance of exposure via the previously mentioned pathways b) the case of WEEE pre-processing facilities. Considered that both lead and cadmium are metals included in the RoHS directive, and that their concentration in WEEE is therefore expected to decrease in time, particular attention should be paid to the case of beryllium. Chronic exposure via inhalation to low levels of Beryllium in ambient air can provoke the chronic beryllium disease (CBD); beryllium is furthermore classified by US EPA as a probable carcinogen for humans via inhalation (Infante, P.F., 2004). The regulatory exposure limit set by the US.EPA agency is a reference concentration (RfC) of 0.02 µg/m^3, a value based on sensitization and progression to CBD (EPA 1998a), while the reference dose (RfD) is 0.002 mg/kg-day. Regarding cancer as endpoint, the inhalation unit risk (upper-bound excess lifetime cancer risk estimated to result from continuous exposure to an agent at a concentration of 1 ug/m^3) calculated by US EPA for beryllium is estimated to be $2.4 \cdot 10^{-3}$ per µg/m^3. In summary, regulatory exposure limits for beryllium already exist, but no further information can be found in the literature regarding the levels of e.g. air concentration of beryllium in WEEE pre-processing facilities. This kind of measurement should be encouraged in order to verify if there is an actual risk from beryllium exposure for the workers of such facilities.

Indium Phosphide

A recent report by the European Chemicals Agency (ECHA, 2010) focuses on risks of Indium phosphide (InP). Indium phosphide is used in semiconductors in electronics, and therefore can be found in WEEE, even if information on concentration levels is missing. For what concerns WEEE treatment, the most relevant and risk-related aspect or indium phosphide is its potential for causing damage to lungs through prolonged or repeated inhalation exposure. Furthermore, indium phosphide is suggested as a class 2 carcinogen. Previous studies, reporting cancer incidence in workers of semiconductors industry, identified indium phosphide as one of the possible carcinogens. Considered that the major route of exposure for workers in Danish WEEE recycling facility is inhalation, and considered the toxicity of Indium phosphide, this compound may represent a concern for workers health. However, it is not possible to quantify this exposure since information on indium phosphide concentration in WEEE is absent.

Gallium Arsenide

Similar considerations are valid for Gallium Arsenide (AsGa). Also for this compound, a recent report by the European Chemicals Agency (ECHA, 2009) summarised the most relevant risks aspects in relation to human exposure. Gallium arsenide is used in the microelectronic industry, where human exposure occurs predominantly for "workers involved in the production of gallium arsenide crystals, ingots and wafers, in grinding and sawing operations, in device fabrication, and in sandblasting and clean-up activities" (ECHA, 2009). Gallium arsenide is typically used in digital mobile phones, personal communication systems, GPS navigation units, satellite and fibre optic communications and wireless networks have driven demand for semiconductor devices manufactured with GaAs (ECCA, 2007). As such a concentration of Gallium Arsenide may consequently be expected, even if quantitative data or information about the levels is missing. Similarly for the case of Indium phosphide, Gallium is considered toxic via chronic inhalation, in particular warrant a classification as T, R48/23: meaning serious damage to health through prolonged exposure through inhalation. However, reproductive toxicity is considered as a more relevant endpoint than carcinogenicity for this compound. Considered the occurrence in WEEE, exposure is expected, even if it can't be quantified due to lack of data. In fact, no data on the amounts used are available and no EEE production or WEEE management exposure scenarios are available.

Americium

Regarding exposure to radiation, the most significant risk may be posed by the presence of americium (americium-241 isotope) in household and industrial smoke detectors, where small amounts of the radionuclide are used in an ionization chamber inside the detector. Americium has a high potential for bioaccumulation, and can persist in the human body for long time, provoking cancer effects due to the fact that it is a highly radioactive element. According to US EPA, it can pose a significant risk for human health if ingested and inhaled (http://www.epa.gov/rpdweb00/radionuclides/americium.html#healtheffects). For what concerns WEEE recycling, risks for workers may be related to inhalation of americium occurring due to accidents or unintentional breakage during the handling of smoke detectors. These devices can in fact be disposed as regular household electronic products and not as radioactive waste, considered that the amount of americium in these devices is small. If not accidentally crashed, dismantled or improperly handled, they don't constitute a risk for human health.

Antimony trioxide

Antimony trioxide (ATO) is used as synergist to enhance flame-inhibiting properties; reduces the amount of halogenated flame retardant used to impart a given level of flame resistance. EU risk assessment of Antimony Trioxide concluded that there is neither risk to the environment or human health nor need for risk reduction strategies other than the existing (EC, 2008). Exposure from several sources was acknowledged but not assessed. Exposure scenarios did not include EEE production or WEEE management work place exposure. The quantity of antimony trioxide imported/exported as a component of finished products, e. g. electrical and electronic articles, is not known (EC, 2008). ATO is classified as carcinogen category 3, denoting that ATO is a substance causing concern but the available data are inadequate to support the evidence of its carcinogenicity in humans (EC, 2008; Environment Canada, 2010).

Germanium

Germanium is one of the rare-earth elements, and represents no concern to health (Roels and Buchet, 2001). According to USGS Mineral Resources Program, silicon-germanium (SiGe) will increasingly replace gallium arsenide (GaAs) in wireless communications devices (Minor metals trade association, http://www.mmta.co.uk).

Brominated Flame Retardants

Various studies have focused on workers exposure to BFR as a category of toxics (Sjodin et al., 2000; Thomsen et al., 2001; Julander et al., 2005). The occurrence in WEEE, the physic/chemical properties and the toxicity of BFR can vary. In general, a common property of BFR is the high persistency into environment and the high potential for bioaccumulation. Furthermore, the thermal treatment of BFR can lead to the formation of dioxins (Watanabe and Sakai, 2003). Sjodin and co-workers (Sjodin et al., 2000) analysed the indoor air concentration of BFR in a Swedish WEEE recycling facilities and found high concentrations. Similar results were obtained by Julander (Julander et al., 2005), referring to Sweden, regarding concentration of BFR in indoor dust of a pre-processing facility. However, only one bio-monitoring study was found regarding workers exposed to BFR from WEEE pre-processing (Thomsen et al., 2001). Thomsen observes how the level of BFR in blood of Norwegian workers from WEEE facilities is higher than the level of workers from other sectors like e.g. PWB production, and this is in particular the case for TBBP-A. Even if scientific evidence of high levels of exposure exists, toxicological studies regarding human impacts attributable to BFR are still in progress. A recent EU-report identified no health effects of concern for TBBP-A (European Chemicals Bureau, 2006), and states that there is no risk for workers in WEEE facilities, based on the exposure levels from the studies mentioned above. According to such study, despite the indications by Gross et al (2008) regarding its hazardousness (the substance is classified by directive 67/548/EEC as R50/53 - very toxic to aquatic species), and despite its potential for bioaccumulation, TBBP-A related risk for workers seem to be limited due to low toxicity to humans. TBBP-A can be used either as additive or reactant in polymers. When it is reacted into the printed wiring board resin, it becomes one of the building blocks for the polymer used for the printed wiring board. This lowers the chances to exposure to pure TBBP-A. However, this is not the case for additive TBBP-A (Sjodin et al., 2000). Regarding HBCCD similar consideration regarding exposure, persistency and bioaccumulation are valid. Also for HBCCD evidences and measurements of toxicity in humans are scarce. Considered their potential for bioaccumulation, and in absence of more specific information on their toxicological behaviour, monitoring in workplaces may be a good policy option from a precautionary perspective.

This suggests that further research is needed both regarding workplace monitoring data (concentration and exposure) on BFR in WEEE pre-processing facilities, but in particular regarding monitoring data on metals. This is of particular relevance since they are the most prevalent chemicals of concern in WEEE, and that information on workers exposure to metals is absent.

7.5 Emissions from end-processing of e-waste sorting residues

Residues from e-waste sorting that can't be recycled or that contain HS are disposed in Danish facilities. Disposal occurs mainly via thermal treatment and in minor part via landfill. In particular:

- Thermal treatment in municipal waste combustion plants with combined heat and power generation, like in the case of the wood fractions, some non-recyclable plastic not containing hazardous substances, and filter residues. Potential e-waste related emissions are polyhalogenated dioxins and furans from incomplete combustion of plastics, and emissions of metal fumes. A number of studies evidenced how the combustion of e-waste increases the emissions of such substances, but mostly agree in saying that appropriate flue-gas treatment technologies can abate efficiently the emissions (Nielsen et al, 2010; Tsydenova and Bengtsson, 2011).
- Thermal treatment in specialized combustion plants dedicated to the treatment of hazardous residues, like in the case of e.g. electrolyte capacitors with PCB, plastic contaminated with hazardous substances, mercury containing switches and mercury-containing components, filter residues. Emissions and hazards are the same as in the case of municipal waste combustion plants.
- Landfill of glass from dismantling of TV sets, and other residual fractions from dismantling. The potential emissions are leaching and evaporation of hazardous substances, metals in particular. Lead and BFR are of main concern regarding leaching, while mercury constitutes a hazard for environment via evaporation (Tsydenova and Bengtsson, 2011).

Apart from these e-waste sorted fractions, an unspecified amount of EEE that is not collected together with WEEE via the municipal collection system ends up in the disposal facilities like municipal waste combustion plants. This is the case for small EEE (e.g. mobile phones, batteries and battery chargers, lamps, etc.) that consumers don't separate from their disposable waste and that can have a complex composition in terms of precious and hazardous substances. There are not published data about the amount of WEEE that is sorted incorrectly and that is collected and disposed together with the municipal waste, or at least such data were not found by the authors. Regarding stockpiling and improper disposal of mobile phones, a recent study by Ongondo and Williams (2011) reports how the quantities of active and stockpiled mobile phones in UK are comparable in magnitude (73 million vs. 50-90 million), but no data on incorrect disposal are available. A screening level survey about consumer's habits has been conducted at NERI in 2010. Results from the survey showed that the amount of WEEE disposed incorrectly is only a minor fraction (<<0.1%) of all the WEEE sold in the

Danish market (see table 3); i.e. between approx. 100-700 tons WEEE per year.

There is at the present time no precise quantification of the impacts on humans and ecosystem due to, or attributable to, the disposal phase of the residual e-waste fractions. The question is whether the hazardous substances introduced in the actual disposal facilities with the sorted waste can ultimately end up in the environment, via which pathways, and in which fraction in terms of input. In their life-cycle assessment study on impacts of WEEE recycling, Hischier and co-workers (Waeger et al., 2011) show that the treatment of specific WEEE fractions, that are contaminated by hazardous substances, has an impact in terms of human and ecotoxicity. However, while the study confirms that e-waste recycling makes sense from an environmental perspective, compared to other management scenarios; it also shows how the disposal of fractions like plastics and capacitors has a potential impact in term of human and ecotoxicity. It is however not specified which of the substances in these fractions are responsible for the impacts.

8 Economic Drivers and Barriers for Recycling

8.1 Economic and energetic aspects

On one hand, recycling of WEEE is promoted by the possibility of recovering precious and valuable metal resources from the e-waste. These can be sold on the metal market with an economic benefit for the treatment facilities. On the other hand, WEEE has to be treated to reduce its content in potentially hazardous substances. Furthermore, the extraction of precious metals from e-waste has a lower environmental impact compared to mining. It is in fact less consuming in terms of energy, water, and land, and produces less emissions (Cui and Forssberg, 2003; UNEP, 2009). The economic and energy drivers for processing metals are either their grade (quality) or their recovery (quantity). Similarly to metals in ore, the cost of metal extraction has to be weighted against the value of the metal contained in the e-waste, in order to determine what fraction can be profitably sorted and what fraction is of too low grade to be worth sorting. Currently, this favours the recovery of valuable resources like Cu that is present both in high grade and high quantities, for example in cables and wires. Furthermore, this also constitutes a barrier for the recovery of the precious metals. In fact, only the fractions like printed wiring boards that have both a high grade and a significant quantity of precious metals are worth separating. On the other hand, the dismantling of other items like e.g. consumer electronic equipment as television sets, video recorders, etc. (also called “brown goods”) gets costly due to the low grade in precious metals and copper of such goods (Cui and Forssberg, 2003). Resource recovery is then prioritized towards metals that can be easily extracted from output WEEE fraction material flows of low grade but significant in terms of quantity. As a consequence, some precious metals are lost during the WEEE sorting and are dispersed in various material output flows.

8.2 Loss of precious metals

Three aspects need to be taken in account regarding the loss of precious metals from WEEE sorting:

1) it is not always possible to separate all metals contained in a specific fraction. An example of efficient metal extraction is the case of printed wiring boards. They can contain high amounts of precious metals, and they are therefore treated in integrated Cu and precious metals smelter-refineries (UNEP, 2009), where each of the metals can be extracted at high rates (see chapter 5). In such case, the extraction of precious metals from the sorted WEEE fraction can be considered as highly efficient. However, precious metals that can for example be found in the aluminium and iron fraction are not recovered. This because such fractions are treated in different facilities: aluminium and iron smelters respectively, which are not designed for extraction of multiple metals.

2) some fractions have to be recycled or disposed via either incineration or landfill. This is for example the case of the plastic fraction that can contain amounts of precious metals. The final treatment of such fraction is not oriented to the metal extraction, so that a loss of valuable resources occurs.
3) as reported by Chancerel et al. (2009), an excessive shredding into small fractions results in a loss of specific special metals like e.g. palladium contained in ceramics (goes to disposal) and parts of printed wiring boards that are magnetically sorted into the ferrous metals fraction.

Because of the growing demand for precious metals e.g. from the Information, Communication and Technology (ICT) sector, and considered their scarcity and the fact that they constitute a constrained resource, a change in the state of the art of WEEE processing is expected to happen in the near future.

In this perspective, the quantification of flows of precious metals in the WEEE management system becomes a priority. In fact, a better knowledge of the concentration and amount of precious metals in e-waste will ultimately highlight what EEE products and what WEEE categories is worth to further treating for extraction of precious metals. Quantitative data regarding the content of precious metals and valuable resources for specific sorted output fractions have been produced by (Morf et al., 2000; Chancerel et al., 2009). Table 19 reports data calculated from (Chancerel et al., 2009) that show the concentration (grade) of precious metals in various different output fractions from a WEEE sorting facility located in Germany where ICT equipment is treated (WEEE fraction nr.3).

Table 20 Concentration of precious metals (Ag, Au and Pd) and of other valuable metal resources (Cu, Al, Fe) in the total input WEEE and in different sorted output fractions from a WEEE sorting facility, in g/ton of sorted fraction. Data have been calculated from values reported in (Chancerel et al., 2009) a) un-shredded; b) pre-shredded; c) shredded; abc) fractions are aggregated. * E.g. Silver in contacts, plugs, or solders.

	Metal concentration (g/ton)					
Sorted fraction	**Ag**	**Au**	**Pd**	**Cu**	**Al**	**Fe**
Unsorted input WEEE	313	22	7	44000	33000	402000
Copper-rich material [abc]	8	2	1	133625	85235	600755
Precious-metals rich material* [abc]	387	62	16	95371	164694	594955
Ferrous metals [abc]	330	27	5	7957	1058	859973
Other material [abc]	90	4	5	20490	10289	74609
Printed wiring boards [abc]	566	94	35	158199	49769	57816
Rubbish and filter dust [ac]	189	14	21	24417	19250	235167
Non-ferrous metals	423	10	5	216000	134000	3000
Aluminium	2722	16	3	33000	408000	7000
Plastics	342	24	9	39000	9000	4000

The importance of these data arises clearly when the fate of the different sorted fractions is considered. If the amount of different output fractions from a specific facility is known, data from table 19 may be used to obtain a rough but indicative estimate of the amount of precious substances that is lost. Furthermore, if the market price of such substances is known, the economic loss can be quantified. In their study, Chancerel and co-workers (2009) estimated that the operators of the German sorting facility do not get any revenue for almost three quarters of the gold and the palladium contained in the input WEEE. Considered that the type of processing is similar between the studied facility and the Danish ones, similar loss of precious metals can be assumed for the Danish context.

8.3 Problematic fractions

WEEE is heterogeneous by nature, because composed by both old and modern products. While the treatment of old EEE products is a consolidated practice, new and emerging products can be problematic to handle. These are reported in Table 20 together with the issues related to their treatment.

Table 21 WEEE fractions those are problematic in the phases from dismantling to mechanical sorting. The issues related to the treatment are reported.

Product	Treatment –related issues
LCD flat screens	Must be dismantled manually and very carefully due to the content of mercury in the light source
Mobile phones, i-pods and similar	Built-in batteries that cannot be easily or immediately removed
Composite material appliances (e.g. enclosures, fiberglass)	Material composed of several layers of different materials and type, separation is not straightforward or possible

One reason of being problematic to handle is that new EEE have increasing complexity both in terms of structure and composition. This requires their collection or separation into dedicated flows that need a special and more advanced, time consuming, and costly treatment. Furthermore, being the appliances composed by a mix of substances, unknown in terms of quantity and type (both precious, hazardous, etc.), it becomes more difficult to extract them separately and to avoid the loss of the precious ones by at the same time assuring a secure handling of the toxic ones. After technical visits to the facilities mentioned in Chapter 4, some types of emerging products were identified as problematic.

9 Conclusions and Perspectives

The present study has analysed the Danish WEEE management system and the environmental issues associated with WEEE treatment in Denmark, with particular focus on the presence of hazardous substances in WEEE.

There is at present time a gap regarding the accounting of flows of electronic products in the WEEE management system: data on EEE produced and imported in Denmark don’t match with data on collected and treated WEEE. This is due to multiple factors: reporting obligations for the private collection sector, stockpiling, and improper disposal of WEEE by consumers. A better quantification of flows of electronics in the system, oriented towards filling the accounting gap, would ultimately improve the management of WEEE by avoiding losses in the system and ensuring sound treatment of WEEE, with consequent benefit for the environment.

Furthermore, better data regarding input /output WEEE fraction flows from Danish collection sites and pre-processing facilities would allow to more precise estimates of the flows of hazardous substances in the WEEE management system, e.g. via the methodologies used in the present report (Material and substance flow analysis). An improvement in the detail and precision of the reporting system and of the available statistics is therefore encouraged.

Treatment of WEEE in Denmark is limited to pre-processing and sorting. Consequently, valuable resources are exported for further recovery, while residues are disposed inside national borders. In this context, it is the interest of the Danish waste treatment facilities that the content of hazardous substances of the fractions to be disposed is reduced, e.g. by a highly efficient sorting.

The RoHS directive restricts six substances. The content of these substances in WEEE is consequently expected to decrease in WEEE in the future. This study identifies other substances of concern based on information from literature. Among these, beryllium and BFR are the most relevant in terms of hazard: the first being carcinogen via inhalation, the others having a high potential for bioaccumulation. However, only poor information on their occurrence in WEEE is available. The substance flow analysis here described provides quantitative information about the actual flows of RoHS and other identified hazardous substances in the WEEE management system. It is obvious that better information regarding presence of hazardous substances in WEEE could be provided by a higher degree of transparency and by a harmonization of the reporting obligations for the EEE producers. This would not only allow the setup of requirements for specific treatment procedures of each individual material/component, like the requirements to manual separation procedures into sub-fractions prior to shredding, but would also allow for deeper and less uncertain calculation with the techniques previously presented (substance flow analysis). This would ultimately lead to an ease in the determination of WEEE treatment-dependent emissions and of their related risks for humans and environment. Such harmonisations of requirements to treatment may at best be delivered by the producers themselves.

The most relevant pathway of human exposure to hazardous substances in WEEE is inhalation of dust from shredding, where the toxic compounds may concentrate. However, both monitoring data on concentration of hazardous substances in ambient air and dust for WEEE pre-processing facilities, and biomonitoring data, are scarce. This constitutes a limit to the assessment of WEEE-treatment related risks. Considered the content of hazardous substances in WEEE, monitoring in the workplace should be improved, with focus on the RoHS substances and on the identified substances: beryllium and BFR.

Last, information on secondary emission from further treatment and disposal of WEEE sorted fraction is absent. Concerns regarding human health related impacts could arise from e.g. the thermal treatment of BFR-containing plastic. This process can potentially generate emission of dioxins, even if existing filtering technologies may prevent completely from this to happen. The quantification of such potential for impact is therefore of great interest and further research is suggested on this field e.g. by means of life-cycle based emission inventories and impact assessment methods.

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Summary

Based on a literature review with focus on hazardous substances in waste electric and electronic equipment (WEEE) and numbers from a Danish treatment facility a flow analysis for specific substances has been conducted. Further, the accessible knowledge on human and environmental effects due to possible emissions from the WEEE treatment is described together with the economic driving forces and barriers for the recycling and use of WEEE for e.g. energy production.

Baseret på en litteratur gennemgang af viden om indholdet af farlige stoffer i affald fra elektrisk og elektronisk udstyr (WEEE) samt tal fra et dansk behandlingsanlæg er der udarbejdet en massestrømsanalyse for udvalgte stoffer. Desuden er den tilgængelige viden omkring humane og miljømæssige konsekvenser i forbindelse med potentielle emissioner fra WEEE behandlingssystemet præsenteret sammen de økonomiske drivkræfter og barrierer for genanvendelse og nyttiggørelse af WEEE til bl.a. energiproduktion.

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