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Chemical Work Environment when Managing and Recycling Waste Electrical and Electronic Equipment

Eirik Aas

PREFACE

This thesis is the final work in my masters' degree in Chemistry and Biotechnology at the Norwegian University of Life Sciences.

I would first like to thank my supervisor Professor Yngvar Thomassen. I would also like to express my gratitude to the people at STAMI for their warm welcome. A special thanks to Eirik Husby, Per Halvard Øveren and Rolf Arne Olsen for agreeing to being interviewed and sharing their knowledge. And lastly where would one be without the support from family and friends.

Eirik Aas
Ås, May 15, 2015

ABSTRACT

Norway generates the most WEEE per capita in the world, the bulk of which is treated in Norway. Several of the processes involved are manual and there is a potential for occupational exposure to the hazardous substances in the WEEE.

The focus of this thesis is to find the available knowledge, both national and international, on the chemical work environment in the management and treatment of WEEE. In addition, we will identify possible knowledge gaps concerning the situation in Norway. To achieve this we use statistics about the amount and treatment of WEEE in Norway, exposure data from Norway, published exposure data from other developed countries and other relevant internationally published information. Most of the research on this subject have been done on the informal recycling of WEEE in developing countries. There are some studies on the conditions found in developed countries, but only exposure assessments and none on adverse health effects. There are good statistics on the volume of treated WEEE in Norway, but only some scarce information on exposure levels in Norway.

Norway follows international trends in the treatment of WEEE, and it is reasonable to expect the concentrations measured in the international literature are representative for the situation in Norway. The measured concentrations, both in Norway and abroad, were generally below the relevant occupational exposure limits. The studies identified a number of new substances of relevance for the chemical work environment. These substances should be considered for inclusion in new exposure studies in Norway. Some studies found a considerable positive effect of preventive measures in the facility to better the chemical work environment. The potential for harmful exposure is present in the management and recycling of WEEE and there is a need for more comprehensive data on the conditions found in these work environments in Norway.

SAMMENDRAG

Norge genererer mest WEEE per innbygger i verden, og mesteparten av dette behandles i Norge. Flere av prosessene er manuelle og det er mulighet for yrkesmessig eksponering av farlige stoffer i EE-avfallet.

Fokuset i denne oppgaven er å kartlegge den tilgjengelige kunnskapen, både nasjonalt og internasjonalt, på kjemisk arbeidsmiljø i forvaltningen og behandling av EE-avfall. I tillegg vil vi identifisere mulige kunnskapshull om situasjonen i Norge. For å oppnå dette bruker vi statistikk om mengden og behandlingen av EE-avfall i Norge, eksponeringsdata fra Norge, publiserte eksponeringsdata fra andre industrialiserte land og annen relevant internasjonal publisert informasjon. Det meste av forskningen på dette temaet har blitt gjort på uformell gjenvinning av EE-avfall i utviklingsland. Det finnes noen studier på de forholdene som finnes i utviklede land, men bare eksponeringsvurderinger og ingen på negative helseeffekter. Det finnes god statistikk på volumet av behandlet EE-avfall i Norge, men lite informasjon om eksponeringsnivåer i Norge.

Norge følger internasjonale trender i behandling av EE-avfall, og det er rimelig å forvente at konsentrasjonene målt i internasjonal litteratur er representative for situasjonen i Norge. De målte konsentrasjoner, både i Norge og i utlandet, var generelt under de aktuelle eksponeringsgrensene. Studiene identifisert en rekke nye stoffer med relevans for kjemisk arbeidsmiljø. Disse stoffene bør vurderes for inkludering i nye studier av eksponering i Norge. Noen studier har funnet en betydelig positiv effekt av forebyggende tiltak i anlegget for å bedre kjemisk arbeidsmiljø. Potensialet for skadelig eksponering er til stede i behandlingen og gjenvinning av EE-avfall, og det er behov for mer omfattende data om forholdene som finnes i disse arbeidsmiljøene i Norge.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

BDE	brominated diphenyl ether
BFR	brominated flame-retardant
CDD	chlorinated dibenzodioxin
CFC	chlorofluorocarbon
EEE	electric and electronic equipment
HBCD	hexabromocyclododecane
LED	light emitting diode
LC	liquid crystal
LCD	liquid crystal display
OECD	Organisation of Economic Co-operation and Development
OEL	occupational exposure levels
PBB	polybrominated biphenyl
PBDE	polybrominated diphenylether
PCB	polychlorinated biphenyl
PCDF	polychlorinated dibenzofuran
PFC	perfluorated organic compound
PFR	phosphorus flame retardant
POP	persistent organic pollution
PVC	polyvinylchloride
ROS	reactive oxygen species
RDF	refuse-derived fuel
RoHS	Restrictions of Hazardous Substances
TBBPA	tetrabromobisphenol A
TBP	tributylphosphate
TBT	tributyltin
TCEP	tris-chloroethylpylphosphate
TCPP	tris-chloroisopropylphosphate
TDCP	tris-dichloroisopropylphosphate
WEEE	waste electrical and electronic equipment

1 INTRODUCTION

Today's standard of living, the quick pace in technological development and the short lifespan of electric and electronic equipment (EEE) all contribute to the fact that the amount of EEE increases three times faster than the amount of ordinary waste [1]. In Europe the waste electrical and electronic equipment (WEEE) waste stream increases with 3-5 % a year [2]. The main challenge with the increase in WEEE is the need to properly handle the hazardous compounds in EEE to minimize the negative impact on man and on the environment. In later years there have been implemented national (Regulations About Recycling and Treatment of Waste) and international legislation (EUs WEEE directive) regarding the collection and treatment of WEEE. The collection rate of WEEE in Europe is shown in figure 1.

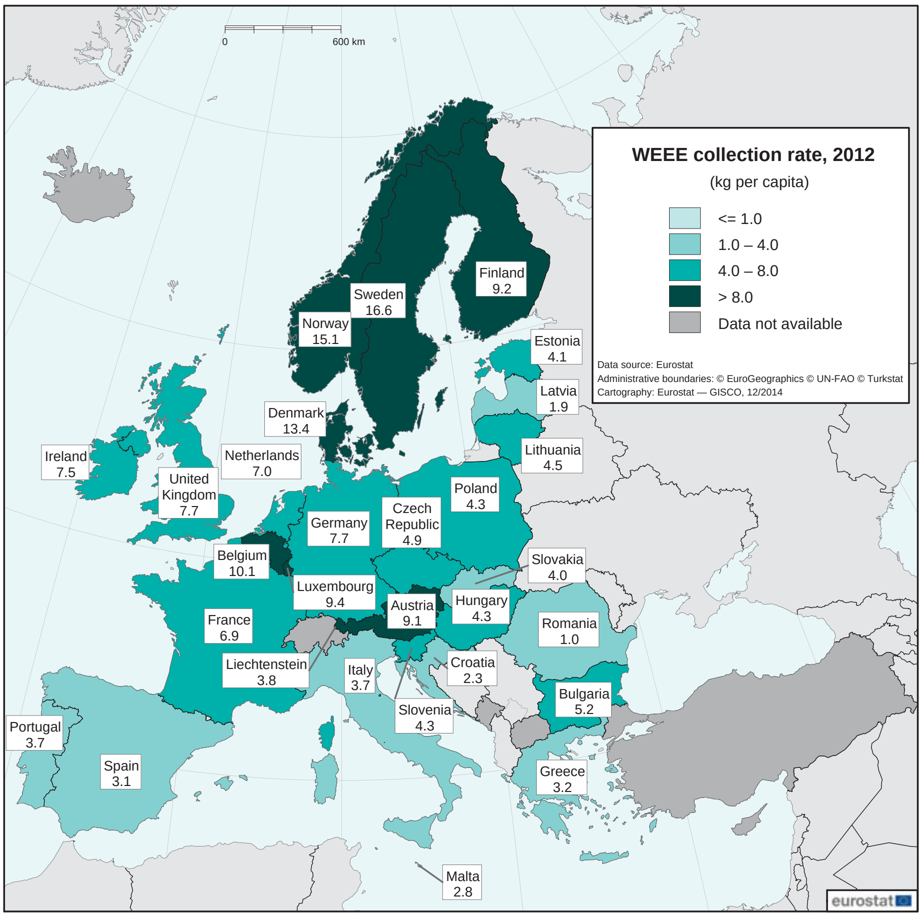


Figure 1: WEEE collection rate in some parts of Europe in 2012 given in kg per capita. Map copied from Eurostat [2].

There is no international accepted definition of WEEE [3]. The most used definition of WEEE is the European Commission Directive 2002/96/EC, which defines WEEE as "Electrical and electronic equipment which is waste, including all components, sub assemblies and consumables, which are part of the product at the time of discarding" [3]. The Organisation of Economic Co-operation and Development (OECD) defines WEEE as "any appliance using an electric power supply that have reached its end-of-life" [3]. In Norway WEEE is defined in the waste regulation as waste EEE [4]. EEE is defined as products and components that is dependent on electrical currents or electromagnetic fields to function correctly, also including instruments to generate, transfer, distribute and measure these currents and fields, including parts necessary for cooling, heating, protection, etc. of the electrical and electronic components [4]. The Norwegian Environmental Authority have been given the authority to make a judgement in any cases of doubts [4].

As a part of the legislation are several requirements about the proper treatment of WEEE where the focus is to recycle (re-use, recover materials or recycle energy) as much as possible. This is not a new sentiment, it has historically been important to preserve valuable materials including valuable parts of waste. In addition to contain a lot of different hazardous substances WEEE is a treasure trove of valuable parts and metals. It is possible to find up to 60 different elements in more complex electronic equipment, and most of these elements are recoverable though all are not economically feasible to extract at the present date [5]. The term "urban mining" refers to the extraction of the valuable components and metals from WEEE [5].

Green chemistry is the modern name of focusing on sustainability. This is done by designing operations and processes to use as few natural resources and hazardous material as possible in addition to being as energy efficient as possible [6]. To minimize the generation of and the negative impact of WEEE, it is important that the producers of EEE not only focuses on phasing out hazardous chemicals, but also have products that are easy to disassemble at the end-of-life [3]. There is also a challenge in the trend of producing products with planned or perceived obsolescence [3].

Some of the benefits of recycling iron and steel WEEE in comparison to extraction and refining virgin materials is shown in table 1. Information about the energy savings of recycling other metals and plastic is listed in table 2.

From time to time the media raises the question about chemical safety. Sometimes the focus is on chemical compounds in consumer goods, where also EEE are discussed [8]. The concern is then about leaching of hazardous chemicals from the product. In the spring of 2015 several big news outlets mentioned a report from the United Nations University where it is calculated that Norway is the country in the world that generates the most WEEE per inhabitant [5, 9, 10].

The focus of this study is on the chemicals that are released when the EEE is recycled. Through the recycling process, the products might be dismantled,

Table 1: Benefits of using scrap iron and steel. Based on information from Cui and Fossenberg, 2003 [7].

BENEFITS	PERCENTAGE
Savings in energy	74
Savings in virgin materials use	90
Reduction in air pollution	86
Reduction in water use	40
Reduction in water pollution	76
Reduction in mining wastes	97

Table 2: Recycled materials energy savings over virgin materials. Based on information from Cui and Fossenberg, 2003 [7].

MATERIALS	ENERGY SAVINGS (%)
Aluminium	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60
Paper	64
Plastics	>80

broken, shredded, melted, and/or incinerated. Dependent on the compound it might be released in several of these stages. Some compounds like dioxins might even be created by the processes and cause occupational exposure [11].

The bulk of the international science about recycling of WEEE is done on the environmental impacts. With regard to occupational exposure the bulk of the research are about the conditions in the informal recycling of WEEE in developing countries and not on the conditions in the formal recycling done in developed countries [3, 11]. What has been researched on the adverse health effects from working with recycling WEEE has primarily been done on workers in the informal recycling industry [11, 12].

The goal of this study is to find and assess national and international knowledge about the chemical work environment in the recycling of WEEE and to assess the situation in Norway and identify possible knowledge gaps.

2 METHOD FOR GATHERING INFORMATION

The focus of this thesis is to identify potential challenges in the chemical work environment for operators working with managing and recycling WEEE in Norway. This is done by assessing the available national and international knowledge. Relevant information were located by using search engines, primarily Google Scholar and Web of Science. Additional information were found by going through the results reference lists. As far as possible, this thesis references the primary source.

In addition to the international research data on the subject, it was necessary to map the extent of recycling of WEEE in Norway. This was done through using the available online resources of the Norwegian Environment Agency. This includes the web page eeregisteret.no. All the companies that work with managing WEEE have to report their activity to this site. All data about the recycling of WEEE in Norway is from 2013. The reason for this is that the data from 2014 where not available before late spring 2015, when this thesis is being written. To fully understand these statistics some questions where asked through e-mail correspondence to the company responsible for managing eeregisteret.no.

The statistics from eeregisteret.no give the amount WEEE collected by the different companies. To further map the situation in Norway and check the relevance of the research, the two different companies were contacted for a possibility for an interview. One where the company responsible for managing the greatest amount of WEEE in Norway, Renas. They are responsible for the treatment of 38 846 tons of the total 144 000 tons, where 25 706 is treated and recycled in Norway and the rest is exported to other countries. The other company is Norsk Gjenvinning. They are one of the contractors that preform the treatment and recycling of WEEE in Norway. They mentions in their promotional material [13] that they have a treatment facility in Drammen where they treat 11 000 tons of WEEE. That is primarly industrial machinery, high voltage equipment, installation material, office equipment and electric tools but they do also treat fluorescent tubes, light bulbs, cables and wires. The Norks Gjenvinning location visited only sorted WEEE before it were sent for further sorting and processing at other facilities. The questions asked Renas and Norsk Gjenvinning in the interviews are listed in appendix A

There were some information concerning air-concentrations and concentrations in biological samples from the industry in Norway. The data are from a database managed by the National Institute of Occupational Health in Norway.

3 RECYCLING OF WEEE

Waste electrical and electronic equipment is diverse and complex, both in the make-up of materials and components. It is therefore important that the WEEE is properly managed after the WEEE has been collected, sorted and shipped to the treatment facility . Hazardous components must be removed alongside the valuable components that are possible to treat or reuse. This is done to decrease the negative impact on the work and the external environment.

There are three major steps in the recycling of WEEE. The first process is the dismantling process. This is necessary to remove reusable components, hazardous materials and valuable components to make it easier to recycle and extract the valuable materials, e.g. from printed circuit boards and copper wires. The next stage is upgrading, where the desirable materials are prepared for further refining through mechanical/physical processing and/or metallurgical processing. The last stage is the refining where the materials is returned to their life cycle. Figure 2 shows a typical process flow diagram of recycling of WEEE.

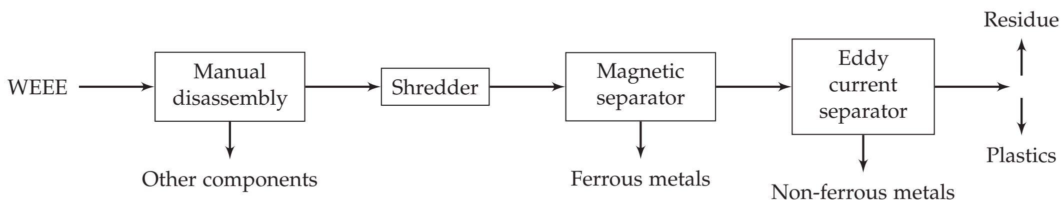


Figure 2: A typical process flow diagrams of recycling of WEEE. [14]

3.1 DISASSEMBLY

The dismantling is primarily a manual process. A schematic overview of the dismantling process and the different fractions is shown in figure 3.

A challenge in the dismantling process is the treatment of brown goods (e. g.television sets, video recorder)[7]. The challenge of recycling these products is that they contain low amounts of precious metals and copper, making it cost-inefficient to dismantle these products manually [7].

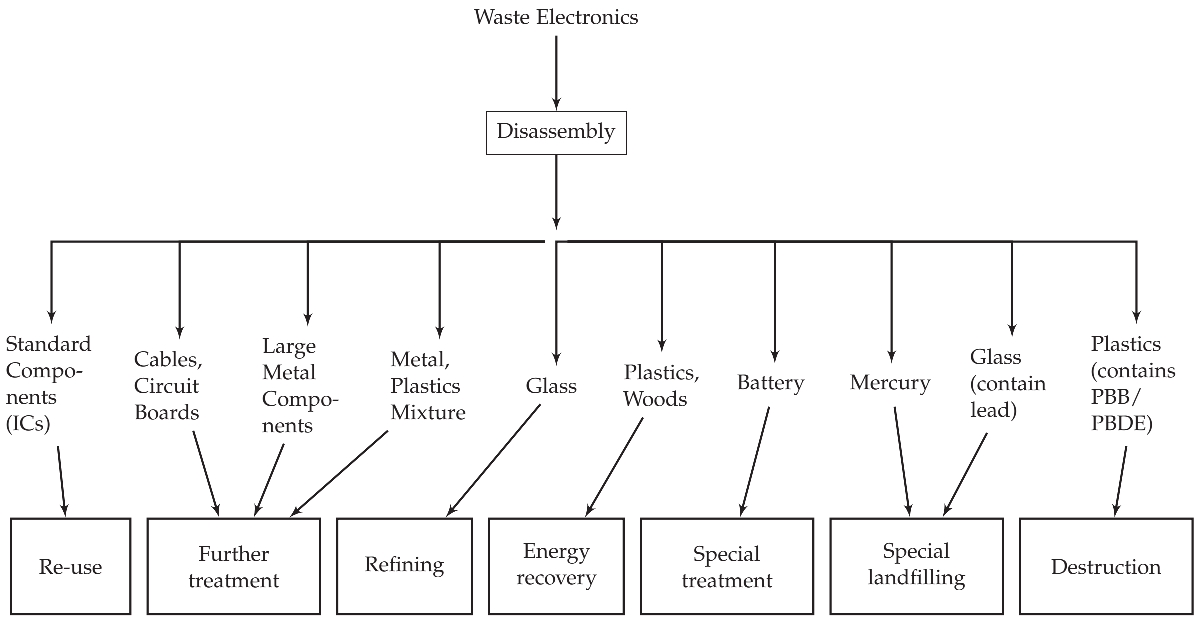


Figure 3: A schematic model of the different fractions separated in a representative dismantling process.[7]

3.2 TYPICAL WEEE RECYCLING METHODS

The first part of the process is the manual disassembly where the focus is to remove parts that either are possible to use again or should be removed before shredding [14]. The different products have their own line where they are manually disassembled [14]. The following examples are of the treatment of household products with large product volume and large number of sales [14].

TV sets: The cathode ray tube is removed and treated separately [14]. The different components are removed and the remaining outer casing is shredded. The metal and plastic are then recovered [14].

Refrigerators: First, the chlorofluorocarbon (CFC) and freezer oil is recovered [14]. Then the other components are removed before the outer casing is shredded [14]. The urethane insulation is removed by using air pressure and then grinded to fine particles[14].

Washing machine: Fully automatic washing machines use salt water as a balancer and this needs to be drained[14]. Then the components are removed, outer casing shredded and plastic and metals recovered [14].

Air conditioners: The CFCs and freezer oil are removed, than the components are removed followed by shredding and recovery of metal and plastic [14].

There are several different technical ways to do the different processes but they all follow the general flow diagram in figure 2.

The fate of the different components and material recovered in the recycling of WEEE is shown in figure 4.

The different recovered metals are submitted to a smelting process without any pre-treatment. The yield of the smelting process is above 95 % of the total amount of metals found in the WEEE [14]. After smelting, the metals are shipped as raw materials [14]. The compressors and motors are manually disassembled where the metals are recovered and the residue is sent to a landfill [14]. The copper wires has the insulation stripped, the plastic landfilled and the metal recovered [14]. The organic compounds in the printed circuit boards are thermally destructed and the different metals are recovered [14]. The glass is recycled into new products by mixing it with virgin materials [14]. The other components are manually disassembled to recover metal and the residue is landfilled [14]. The plastic is made into pellets and converted to refuse-derived fuel (RDF) [14]. This process has an efficiency of extracting 60-70 % of the available energy.

3.3 Metallurgical recovery of metals from WEEE

Several different main principles can be applied to recover the metals from WEEE [15]. The traditional method of recovering the metals have been through pyrometallurgical processes. There are some of these processes that utilize the energy in the plastic. Thermal systems is a viable way to extract metals as long as a comprehensible emission system is installed [15]. A different method is to extract the metals through hydrometallurgical methods where the metals are dissolved using either acid or caustic leaching [15]. The last main method that is discussed is bioleaching but there is still need for further research into the efficiency of this method [15]. Figure 5 show a proposed process flow for a hydrometallurgicaly extracting metals from WEEE.

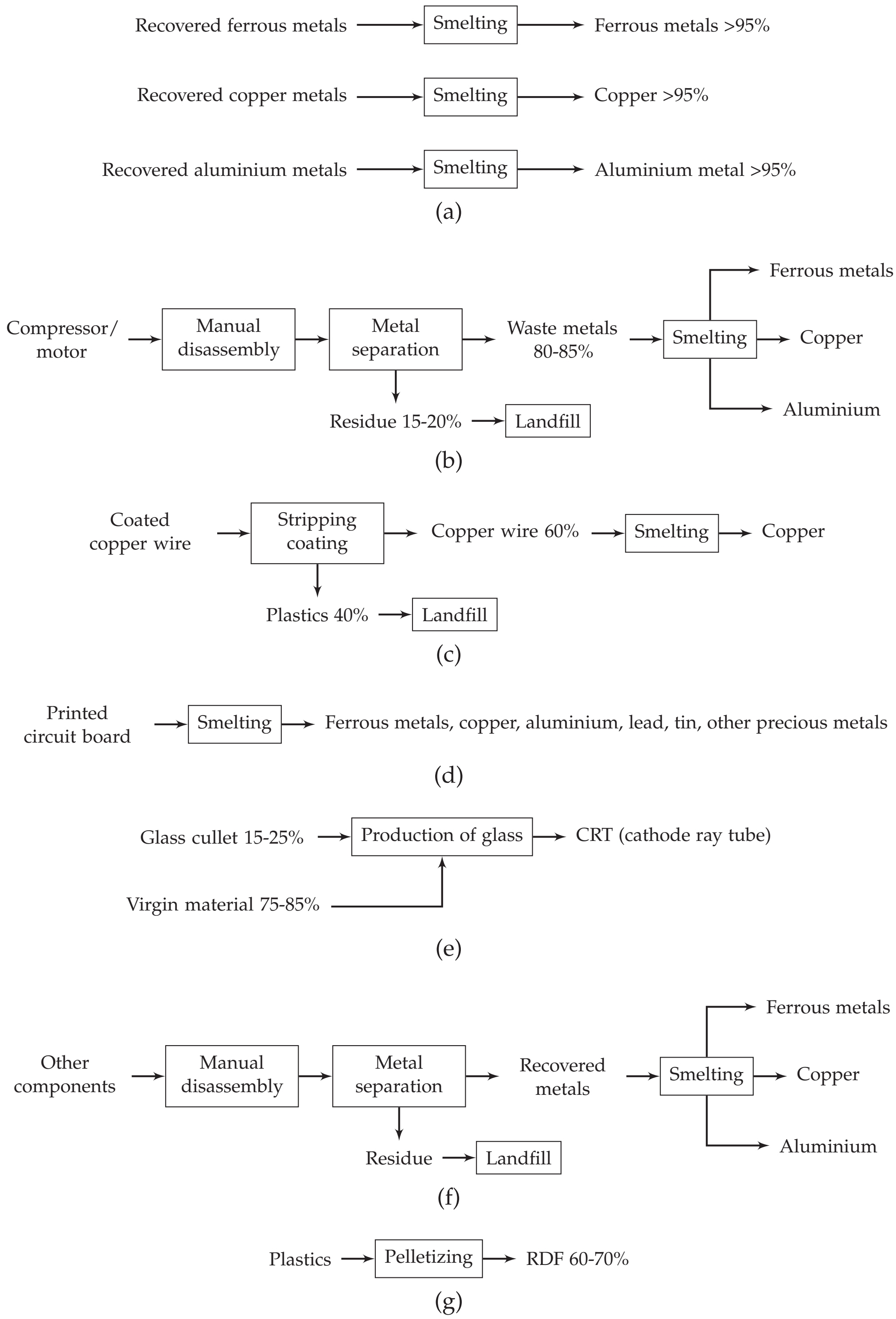


Figure 4: Further treatment of components and material recovered in a recycling process. a) The fate of the metal fractions. Further treatment of b) compressors and motors, c) coated copper wires, d) Printed circuit boards, e) Glass cullets, f) other components, g) plastics [14].

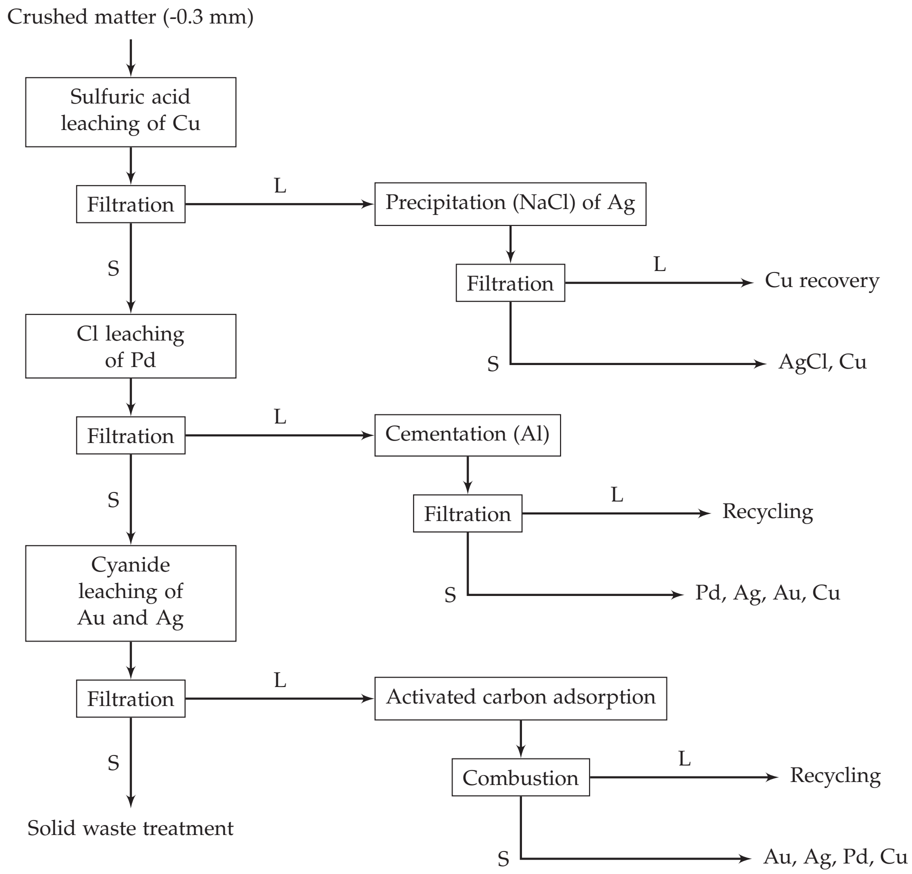


Figure 5: A suggested process flow for hydrometallurgical recovery of metals from WEEE. The figure shows the path and further treatment of the solid (S) and liquid (L) fractions in the different steps.[15]

4 HAZARD IDENTIFICATION

EEE is a heterogeneous mix of different parts and components. This is also true about its chemical makeup [11]. Not all chemicals are toxic to humans and those that are vary greatly with regard to bioavailability, mobility, degradability, and toxicity [16]. The Silicon Valley Toxics Coalition reports that just one computer can contain hundreds of chemical compounds. This includes toxic compounds like lead, mercury, cadmium, brominated flame-retardant (BFR) and polyvinylchloride (PVC) [17]. The Norwegian Environmental Authority states that most EEE contains one or more hazardous chemical compounds [1].

4.1 HAZARDOUS SUBSTANCES IN WEEE

There are three groups of compounds that the workers in the management and recycling of WEEE might be exposed to [3]:

- Substances originally a part of the EEE
- Substances added during treatment
- Substances that are formed during the treatment

This thesis focuses mainly on substances in the WEEE that might be released, and mention some that may be formed through the process. As a result of the strict rules in Norway about the use of chemicals and the requirement about risk assessment of the different processes the substances added as a part of the treatment should be an obvious source of exposure and should be adequately known by the businesses that use them.

The RoHS regulates the use of the following compounds found in WEEE: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenylether (PBDE) [18]. But there are identified above 1000 different chemicals in WEEE where there is little or no knowledge regarding their toxicity and environmental effects [3].

Hazardous substances that can be found in WEEE are:

- Americium are used as radioactive source in smoke detectors [18].
- Antimony might be found in printed circuit boards and cathode ray tubes [19]
- Arsenic might be found in transistors and light emitting diode (LED) [19]

- Beryllium might be found in thermal interface materials and printed circuit boards [18, 19, 19, 20].
- BFRs found in the plastic in most EEE [18, 19, 20].
- Cadmium found in nickel-cadmium batteries and some alloys [18, 20].
- Chlorofluoratedcarbons might be found in old refrigerators and coolers [3].
- Chromium might be found in nearly all WEEE [19].
- Cobalt might be found in batteries and hard-drives [19].
- Dioxins might be created in the thermal processing of plastic containing chlorine [3].
- Indium might be found in liquid crystal display (LCD)-screens and silicon chips [3].
- Lead might be found in solder, cathode ray tubes, batteries, LED and some formulations of PVC [18, 20]
- Lithium might be found in rechargeable batteries [19].
- liquid crystal (LC) used in LCD [21].
- Manganese might be found in batteries [19].
- Mercury found in LCD-screen and tilt-switches [18, 20].
- Nickel might be found in most electronics and batteries [19].
- Palladium might be found in most electronics [19].
- Phthalates might be found as softener in plastic [20].
- polychlorinated biphenyls (PCBs) might be found as insulation material
- PVC [19, 20].
- Ruthenium might be found in electrical contacts and chip resistors [19].
- Selenium might be found in printed circuit boards and photosensitice equipment [19].
- Sulphur found in lead-acid batteries [18, 19].
- Tantalum might be found in capacitors [19].
- Thallium might be found in batteries and semiconductors [19].
- Tin might be found in solder [19].
- Zinc might be found in most electronic products [19].

A challenge in identifying the hazardous substances are the ghost effect. This effect is when hazardous substances have not been properly removed and are found in recycled materials [22, 23]. An example of this is the results from a study that identified PCB, that should have been faced out, in recycled plastic [22, 23].

4.2 inorganic compounds

Inorganic compounds are all metals and other elemental substances. Common for them all is that they cannot be degraded; only their chemical speciation might change through chemical reactions. A typical reaction that change the chemical speciation is redox reactions. Some metals are nutritionally important for the human body to function, essential metals/compounds (e.g. chromium, copper, zinc [24]). Some are only needed in small amounts (essential trace elements). The different compounds are required in different amounts, and lack of dietary intake of these compounds might cause adverse health effects. This study will only look at the adverse health effects from increased exposure.

The human body have several systems to cope with exposure to inorganic substances. One of these systems is the protein metallothionein. Metallothionein is a protein that binds to the toxic metals to immobilise them, and then transport the toxic metals to the kidney where they are stored. This means that the body has a threshold limit before the exposure to toxic metals cause adverse health effects.

4.2.1 *Arsenic*

Today arsenic is mostly used in metal alloys, semiconductors, solar panels and electronics [16]. The use of arsenic in Norway in 2007 was 42 tons [16].

Arsenic is a metalloid that in its inorganic form is a potent toxin while as part of an organic molecule its toxicity is decreased [16, 25]. Arsenic exposure by ingestion or inhalation is considered toxic for humans and might cause cancer [16, 25].

The use of arsenic and arsenic containing compounds is regulated through REACH Appendix XVII [25]. Seven arsenic containing compounds are on the European watch list, meaning that the producers that use these compounds have stricter information requirements [25].

4.2.2 *Cadmium*

Cadmium is a common compound in batteries (Nickel-Cadmium (NiCd) batteries), solar cells, solder alloys, cadmium vapour lamps, old television tubes [16, 26]. In 2007 13 tons of cadmium were used in Norway, where 98 % were used in batteries. NiCd batteries are used less than before and are being replaced by other batteries in all products other than electric tools [16]. It is no longer allowed to use cadmium in paint, packaging, EEE, and portable cadmium batteries [27]. The exemption from this is when used in electric tools [16].

Cadmium is acute and chronic toxic for humans [27]. Cadmium will accumulate in the body, especially in the kidneys, and it has a long biological half-life of 20-30 years [16, 27, 28]. In reality, humans accumulate cadmium their entire life [27]. Inhalation exposure to cadmium is considered very toxic [27].

The reaction mechanism of cadmium in the body is not known but it is assumed that the adverse health effects are a result of the fact that cadmium 2+ have a similar size to calcium and zinc and might replace them [26, 29]. Another theory is that cadmium induces reactive oxygen species (ROS) which in turn interfere with metabolism. This theory is partly supported by another study that claim that the toxicity of cadmium is caused by lipid peroxidation and other ROS. They also claim that cadmium inhibits the body's defences against lipid peroxidation the glutathione peroxidases.

Exposure of above 10 mg cause acute adverse health effects [26]. Cadmium damages the kidneys, cardiac tissue, bones and is a carcinogen [27]. It is suspected that even low-level cadmium exposure can increase the risks for cardiovascular diseases [16, 27]. The first symptom is the excretion of small protein as retinol-binding protein in urine caused by damage to the tubules which are no longer able to reabsorb these proteins [26]. Other symptoms for cadmium exposure is salivation, choking, vomiting, metallic taste, loss of sense of smell and joint pains [26].

4.2.3 *Chromium*

The use of Chromium in WEEE where banned in 2006 [30].

Chromium is an essential trace metal and is mainly found in two different chemical species, trivalent and hexavalent [16]. As with other metals redox conditions or pH might change the chemical speciation. Pure chromium have no effect on the human body [30]. Trivalent is considered relatively safe while hexavalent have the ability to bioaccumulate, have long biological half-life and might cause allergies and/or cancer [16, 30]. Soluble cadmium compounds might cause corrosive damage and exposure through ingestion might cause damage to the kidneys and liver [30]. Several compounds containing chromium are considered to be carcinogens and harmful for the reproductive system [30].

The European Restrictions of Hazardous Substances (RoHS) prohibits the use of hexavalent chromium in EEE in the EEA-area [16].

4.2.4 *Lead*

Lead is an element that has been found in several different useful products throughout the ages such as sweetener, pipes, paint and gasoline additive. In the 2^{nd} century BCE Discorides said that "Lead makes the mind go away"

[31]. In electrical and electronic equipment lead is used in batteries, plastic (stabilizing PVC), and solder [31]. A ban has been implemented on the use of lead in packaging, EEE, cars and toys [16].

Lead is one of the most studied hazardous compounds in the 20^{th} century [31]. Lead is not essential and has no limits that are necessary for the human body. Lead can have an effect on several processes in the human body. A focus has been on the adverse effect on the new production of haemoglobin, which can lead to anaemia [16]. Lead is also proven to adversely affect the nervous system, the immune system, and reduce the mental development of children [16, 32].

Lead can be inhaled as a particles, or ingested. When ingested, children absorb approximately 50 % while adults absorb only around 5-10 % [33]. This is because children have a greater demand for calcium and iron, and lead with its approximately same size and charge density is absorbed alongside these elements.

Lead is distributed in several different parts of the body. Lead that is located in the blood stream attaches itself to the red blood cells and has a biological half-life of about 25 days. As mentioned lead mirrors the behaviour of calcium in the body, and lead is therefore found both in muscles and in bone. In muscles, lead has a half-life of about 40 days while it is much more stable stored in bone where it has a half-life of about 10 years [33]. Humans accumulate lead throughout our lives, particularly in our bones as youths, and 95 % of the lead in adults is found in our teeth and bones [34].

The most common biomarker of exposure to lead is the blood level where it is measured as micrograms per one decilitre of blood (µg/dL) [35]. The regulated limit of lead in the blood of workers in Norway is 1,5 mikromolperliter (0,5 mikromolperliter for women in fertile age)[36]. The most sensitive part of the body for lead poisoning is the nervous system. At high levels of lead the brain will swell (encephalopathy) which can result in death [35]. It has been documented that lead has caused damage to the peripheral nervous system in adults that worked as painters using paint containing lead. There is evidence that show that adults experience a decrease in their cognitive performance at blood lead levels at 25 µg/dL [35]. Another common adverse health effect from exposure to lead is a result from the lead associating to the red blood cells. When lead is present in the blood stream haemoglobin synthesis is impaired and the red blood cells becomes more fragile. This can result in anaemia. Lead also has an adverse effect on the kidneys and several studies show a relationship between elevated lead exposure and elevated blood pressure and a weak link between elevated exposure and lung and brain cancer. Lead also pose a risk to the reproductive system for both males and females.

4.2.5 *Mercury*

Mercury is the only metal that is liquid at room temperature. Pure mercury has a high density, 13,6 times that of water. Mercury has a low boiling point and high vapour pressure and will therefore slowly evaporate at room temperature [37]. In EEE mercury is found in fluorescent bulbs, switches, thermometers, manometers and button batteries. After EU banned incandescent bulbs in 2012, the amount of recycled mercury containing bulbs is expected to grow [16].

Inorganic mercury can be biotransformed by microorganisms to an organic specie (methyl mercury, Met-Hg) [16, 37]. The methyl group makes the compound more lipophilic and methylmercury will therefore be stored in the fatty tissue and have the ability to bioaccumulate and biomagnify in the food web [37].

Exposure to methylmercury (Met-Hg) may cause adverse mental effects and cause motoric afflictions as a result from damage to the central nervous system [16, 38]. Inorganic mercury accumulate in the kidneys but might also cause allergies and might damage the foetus [38]. Both inorganic and organic species of mercury have a long biological half-life [38]. Inorganic mercury causes the most harmful effects when inhaled as a mercury vapour. The vapour easily enters the bloodstream and is transported throughout the body and it is able to cross both the blood-brain barrier and the placenta. If the mercury is transported across the blood-brain barrier it might be oxidized. After being oxidized the charge prevents the mercury from being transported back intro the bloodstream. With continuous exposure, mercury will accumulate in the nervous system leading to potentially debilitating nervous system afflictions [37].

Adverse effects after exposure to methylmercury have been much more common. Mercury is a developmental toxin and the U.S National Research Council states, "60 000 newborns annually may be at risk for adverse neurodevelopmental effects from in uteroeexposure to methylmercury" [37].

The symptoms of exposure becomes apparent after a latency period where there are not observed any effects. The higher the dose of the exposure, the shorter is the latency period before the symptoms appear. Occupational threshold limit for mercury in urine is in Norway 30 μg/g creatinine [36]

4.3 ORGANIC COMPOUNDS

Organic compounds is all compounds with a carbon skeleton. The organic compounds are produced naturally or artificially. As with the inorganic compounds, the organic compounds have a wide range of properties, but in contrast the organic compounds might be degraded in nature. This is done either biologically or through physiochemical reactions. The different degradation reactions or recycling processes might even create some hazardous organic compounds, like dioxins. The rate of degradation is different from compound to compound. This is also true about the biological half-life. The human body have different systems to deal with different compounds, and the systems has different efficiencies.

Lipophilic compounds generally bioaccumulate and the compounds must first be made more hydrophilic before the body is able to excrete the compound. These reactions in the body can also influence the toxicity of the substance; some compounds might even become toxic after the compounds is made more hydrophilic. This phenomenon this is called bioactivation.

4.3.1 *Dioxin*

All dioxins are organochlorine compounds and the term dioxin covers eight chlorinated dibenzodioxins (CDDs), ten polychlorinated dibenzofurans (PCDFs) and twelve PCBs [39]. The difference between these compounds is the placement and number of chlorine atoms but they have similar properties and reaction mechanisms [16, 39].

All dioxins are highly lipophilic and difficult to biologically degrade but are more sensitive to photochemical degradation [40]. There is more than hundred different compounds with a different degree of chlorination that are covered by these two groups of compounds [16]. Dioxins are unwanted by-products of incomplete combustion of organic material where chlorine is present and is produced naturally in forest fires or volcanic activity [16, 40]. There are also anthropogenic sources like industrial, municipal and domestic incineration and combustions processes. The anthropogenic sources are considered the most significant sources [39]. Dioxins are covered by the Stockholm convention, protocol for persistent organic pollution (POP) [16]. Dioxins are relevant for the chemical work environment in the incineration of the different types of plastics containing chlorine.

Exposure to dioxins can take the form as inhalation of dust, through the skin or by ingestion [39]. To excrete dioxins the compound must be transported to the liver where it is transformed to a more water soluble compound. Dioxins is slowly metabolised and tend to bioaccumulate, in the fat and liver [16]. The speed of elimination vary with dose, amount of body fat, age and sex [39].

Dioxins is acutely toxic for some organisms, but humans are not among those [16]. Animal studies have shown that a foetus exposure to low levels of dioxins might cause reproductive harm and harm the immune system. Some dioxins are considered endocrine disruptors and/or carcinogens [16, 39]. Proven effects of exposure to dioxins for humans are adverse effects on the immune system, irritation of the skin and a skin condition called chloracne [16, 39]. Dioxin might also be a carcinogen for humans. The main exposure of dioxins to humans is dietary exposure from eating fish and animal fat [16].

Dioxins might have an acute adverse health effect where a short time exposure to (2,3,7,8 TCDD) can cause chloracne, redness and pain [39]. In addition 2,3,7,8 TCDD is also listed as a known carcinogen by IARC (International agency of Reaserch on Cancer) and as a endocrine disruptive compound in the European Union Prioritization List [39]. It have also been shown in studies with laboratory animals to be linked to endometrioses (adverse effect on the uterous), developmental and neurobehavior effects (learning disabilities), developmental effects on the reproductive system (decreased sperm count, malformation of the genitals) and immunotoxic effects [39, 41].

4.3.2 *Polychlorinated biphenyls*

PCBs are mostly found in mixtures with up to two hundred congeners with different numbers and placement of chlorine atoms [16, 42]. PCBs were made illegal to use in Norway in 1980 [16]. PCBs were formally used in transformers, capacitors and other EEE [16]. All lighting fixtures containing PCB should have been decommissioned and delivered as hazardous waste in 2008 [16, 42]).

PCBs are difficult to degrade and is highly lipophilic and therefore biomagnifies in the food web [16, 42]. Since PCBs biomagnify, humans are exposed to PCBs through dietary intake of animals products containing PCBs, and it is even possible that PCBs are transferred to the next generations through the placenta and breast milk [16, 42]. Many of the PCBs and their metabolites are considered endocrine disruptors caused by their similarity to different hormones in the body and they might influence the enzymes responsible for degrading the hormones [16, 42, 43]. Exposure to PCBs might also have an adverse effect on the immune system, harm the nervous system, cause liver cancer, reproductive harm, and have developmental effects by negatively influencing childrens capabilities to learn [16, 42].

4.3.3 *Brominated organic compounds*

Brominated organic compounds is a term that covers all organic compounds containing bromine [16]. The main use of brominated compounds is as BFRs. When brominated organic compounds are exposed to heat, they release bromine radicals that terminates the chain reactions in combustion reactions [16]. There are approximately 70 different brominated organic compounds that are used as flame-retardants and the different compounds may have completely different properties with regard to bioavailability, distribution and effects [16]. It is calculated that in 2007, there was used 450 tons of five different BFRs.

The main contributors to this was tetrabromobisphenol A (TBBPA) at 293 tons, deka-BDE (brominated diphenyl ether) at 114 tons and hexabromocyclododecane (HBCD) at 43 tons. Of the total use of BFRs, 340 were used as flame-retardants in EEE. Among the different sources that releases BFRs are shredding installations [16].

When analysing blood and breast milk in the general human population several BFRs were found. The sources to the general population are house dust, vapours from EEE and dietary exposure.

- Penta-BDE is difficult to degrade, it bioaccumulates and is an endocrine disruptor. [44].
- Okta-BDE is classified as harmful for the reproductive system and harmful for the foetus [16, 44].
- Deka-BDE may harm the nervous system and can be metabolised to the more harmful okta-BDE [16, 44].
- HBCD is difficult to degrade but is mainly harmful to aquatic organisms [16, 44].
- TBBPA is also difficult to degrade and is an endocrine disruptor [16]. In the environment, TBBPA may be degraded to bisphenol A [16, 44].

There is a lack of knowledge about the toxicity or possible endocrine disruptive effects for many of the BFRs [16].

The use of penta-BDE and okta-BDE was prohibited in 2002 and a prohibition to use deka-BDE followed in 2008 [16, 44]. These compounds is also covered by the Stockholm convention [16, 44]. But these compounds are still found in older products, and the products that contain more than 0,25 weight percent is considered to be hazardous waste by the RoHS legislation and it is required that in the recycling of WEEE the components that contain BFRs are removed before further processing [16].

4.3.4 *Perfluorated organic compounds and phosphorus flame retardants*

This term applies to several hundred compounds [16]. Most of the perfluorated organic compounds (PFCs) are both lipophilic and hydrophilic. Some PFCs functions as flame-retardants. There is a huge difference in the amount of knowledge with regard to use and amounts for the different compounds [16]. PFCs are among other things used as a heat exchange medium in the production of transistors and other semiconductors and as a softener and flame retarder in plastic [16, 45]. There are two PFCs in the governments watch list, PFOS and PFOA [16, 45]. The focus on these compounds have also lead to an increased focus on other PFCs [16, 45].

The main routes of exposure to PFCs are through ingestion of food and drinking water and inhalation of dust and indoor air [16, 45]. Contrary to most other organic compounds that accumulate in the fatty tissue, PFCs are mostly bound to proteins and accumulates in the liver and in the blood [16].

A sediment sample from outside a shredding facility contained phosphorus flame retardants (PFRs) [16]. The PFR that was found to be the most abundant was tris-chloroisopropylphosphate (TCPP) [16]).

A mapping for the four most common PFRs (tris-chloroethylpylphosphate (TCEP), tris-dichloroisopropylphosphate (TDCP), tributyltin (TBT) and TCPP) showed that all of these with the exemption of tributylphosphate (TBP) were classified as difficult to degrade [16]. TCEP is considered chronically toxic and assumed to be harmful to the reproductive system [16, 45]. Animal studies showed that chronic exposure to TCEP, TDCP and TBP cause neurological damage [16]. None of these PFRs was found to biomagnify [16].

4.3.5 *Bisphenol A*

Bisphenol A is used as a component in making plastic. Exposure to bisphenyl A is mainly through residue of bisphenol A monomers that did not react completely when the plastic where formed.

Bisphenol A is easily degradable in water, does not to any great extent bioaccumulate and is an estrogen [16, 43, 46]. Since it is a estrogenic it is considered to be an endocrine disruptor and harmful for the reproductive system and the development of the unborn child [43, 46]. It is also classified as harmful for the eyes, irritating to the mucous membrane and it is an allergen with skin contact [46].

The measured concentrations of bisphenol A in saliva is considered to be too low to cause adverse health effects in the short term, but there is some concern with regard effects from long term exposure [16].

4.3.6 *Phthalates*

Phthalates is the term for a group of organic substances that are mainly used as a softener in plastics [16]. It is among other things often found in PVC that are used to isolate cables [16].

As a softener in plastic phthalates is not chemically bound to the plastic and will in time diffuse out of the plastic and make it more brittle [16]. This means that plastic containing phthalates will leak phthalates to the surrounding environment. Even though plastic containing phthalates leak to the surrounding environment it is still considered that the main source for phthalates exposure is through diatary intake, and then exposure in the indoor air. The main source for phthalates in the indoor environment is considered to be from phthalates containing products. An example of a product containing phthalates is flooring. The use of phthalates has been declining after it was documented that they might cause adverse health effects and their use is now closely regulated [16].

Phthalates are relatively easily degradable in water and bioaccumulate differently in different organisms [47]. The difference in the degree of bioaccumulation is a result of different organisms ability to degrade and excrete Phthalates.

Phthalates are suspected to act as an endocrine disruptor and it is possibly carcinogen [16, 43]. Phthalates are considered to be easily degraded in the human body. The group most sensitive to Phthalates exposure are small children.

4.3.7 *Polyvinyl Chloride*

PVC is the organochlorine that is produced in the greatest volume [48]. PVC is extremely difficult to recycle because it is a mixture of PVC and additives, and the mixture differs between the different applications [48]. If the PVC is only deposited to a landfill, the PVC might leech out toxic additives [48].

Elements that are known to have been used as additives in PVC are arsenic, bromine, calcium, chlorine, copper, iron, lead, manganese, silver, strontium, tin, titanium and zinc [48].

Incineration of PVC might create dioxins.

4.3.8 *Liquid Crystals*

The compounds used in LCD are mixture of different compounds belonging to the group of substituted phenylcyclohexanes, alkylbenzenes and cyclohexylbenzenes [21]. These compounds are used as electroactive layers that compose the LCD.

There have been done toxicological studies on single LCs [21]. So fare these studies have only found some LC that are irritating, corrosive or sensitising properties to skin [21]. So fare there have not been any indications of a carcinogenic effect or any oral acute toxicity [21].

5 AVAILABLE EXPOSURE DATA

This chapter lists and gives information about available exposure data. Most of the available data about exposure for workers working with recycling of WEEE are from the informal recycling industry, mainly from south-east China [12]. There are some studies and reports looking at the conditions in the formal recycling industry.

Inorganic elements:

- "Formal recycling of e-waste leads to increased exposure to toxic metals: An occupational exposure study from Sweden" [49]
- "Release of Mercury from Broken Fluorescent Bulbs" [50]
- "Occupational exposure in the fluorescent lamp recycling sector France" [51]
- "Exposure to Hazardous Metals During Electronics Recycling at Four UNICOR Facilities" [52]
- "A Pilot Assessment of Occupational Health Hazards in the U.S. Electronic Scrap Recycling Industry" [53]
- "Evaluation of Occupational Exposure at an Electronic Scrap Recycling Facility" [54]

Organic substances:

- "Brominated Flame Retardants in Waste Electrical and Electronic Equipment: Substance Flow in a Recycling Plant" [55]
- "Exposure to Flame Retardants in Electric Recycling Sites" [56]
- "Flame Retardants Exposure: Polybrominated Diphenyl Ethers in Blood from Swedish workers" [57]
- "Flame Retardants in Indoor Air at an Electronic Recycling Plant and at Other Work Environments" [58]
- "Polybrominated diphenyl ether exposure to electronics recycling workers - a follow up study - a follow up study" [59]

There are also some reports made by different agencies that also mention relevant information concerning the exposures in formal WEEE recycling in different countries.

Reports:

- "WEEE and Hazardous Waste" [21]
- "The global impact of E-Waste - Addressing the challenge" [3]
- "Review of Health Risks for workers in the Waste and Recycling Industry" [60]
- "The WEEE Report - Waste Electrical and Electronic Equipment Reuse and Recycling in Canada - 2013" [61]

Generally stated the different studies and reports show a clear potential for hazardous exposure, but the concentrations for the studied substances were below the different countries occupational exposure levelss (OELs).

Table 3 and table 4 show the available data on the chemical work environment in the management and recycling of WEEE in Norway. There were also some data available on the air concentrations of some elements, but too many of the values were detected but not quantifiable for the results to be summarized in a table. The available data were generally a couple of measurements from the same facility at different locations and measured in couple of different years.

As the table show there are not that many measurements available, and most of the measurements are from different companies, processes and years. The data that have been pooled in the table may not give a representative result given that the different locations might process different WEEE and therefore it might be expected a difference in the chemicals present in the work environment. Another weakness is the fact that different years in the same facility have also been pooled. There were not enough data to look at any trends in the exposure at the different facilities, and any possible trends are not accounted for in table 3 and 4.

Table 3: Measurements of organic solvents at different companies in Norway. Exposure data from the expo.-database.

	Collecting of Hazardous waste			Collecting of non-hazardous waste			Treatment and disposal		
Compund	**N**	**Geometric mean (ppm)**	**Range (ppm)**	**N**	**Geometric mean (ppm)**	**Range (ppm)**	**N**	**Geometric mean (ppm)**	**Range (ppm)**
1,1,1-trikloretan	5	0,268	0,03-1,73	0			0		
1,2,4-trimetylbenzen	6	0,072	0,023-0,159	0			0		
2-butoksyetanol	12	0,099	0,063-0,164	0			0		
2-propanol ppm	15	0,241	0,057-1,065	14	0,233	0,005-43,669	16	0,519	0,081-3,972
4-metyl-2-pentanon	0			6	0,050	0,008-1,907	0		
Aceton	12	0,188	0,049-2,088	3	15,924	10,09-39,659	3	19,633	1,776-149,291
Alifater C3-C4	12	0,601	0,067-11,649	0			0		
Alifater C4-C8	0			7	0,227	0,123-0,374	4	4,231	1,203-14,921
Alifater C5-C8	18	0,410	0,081-8,048	14	0,598	0,063-66,591	14	2,469	0,205-86,193
Alifater C9-C13	18	0,804	0,079-3,834	21	0,385	0,03-8,307	16	0,535	0,082-4,037
Aromater C9-C12	6	0,226	0,095-0,456	0			0		
Benzen	0			1	0,981	0,981-0,981	0		
Butanon	3	0,561	0,358-0,718	2	0,390	0,166-0,915	0		
Diklormetan	5	2,891	0,8-10,2	0			0		
Etanol	0			14	0,301	0,023-6,203	8	0,171	0,022-2,597
Etylacetat	20	0,131	0,003-3,69	1	2,059	2,059-2,059	6	0,234	0,015-1,646
Etylbenzen	29	0,053	0,009-0,376	19	0,028	0,004-0,499	20	0,159	0,02-1,059
Freon 113	2	0,841	0,6-1,18	0			0		
m&p-xylen	30	0,135	0,013-1,137	20	0,082	0,007-1,382	20	0,393	0,037-3,512
n-butanol	2	0,025	0,006-0,105	0			0		
n-butylacetat	14	0,194	0,04-2,278	3	0,372	0,337-0,453	20	0,114	0,008-10,44
o-xylen	30	0,036	0,006-0,36	20	0,028	0,004-0,53	20	0,103	0,012-0,852
Tetrakloretylen	8	0,433	0,04-2,77	0			0		
Toluen	30	0,176	0,016-2,36	23	0,084	0,01-3,252	20	0,262	0,011-9,725
Trikloretylen	7	0,447	0,147-2,59	0			0		
VOC I	12	1,900	0,47-7,13	0			0		
VOC II	12	0,236	0,04-0,75	0			0		

Table 4: Measurements of some elements in biological samples at different companies in Norway. Exposure data from the expo.-database.

	Sorting and treatment of waste before material recycling			Dismantling		
	N	GM (umol/l)	Range (umol/l)	N	GM (umol/l)	Range (umol/l)
B-Cd nmol/l	144	$4,719 \times 10^{-3}$	$(0,4-71) \times 10^{-3}$	0		
B-Hg nmol/l	143	$9,681 \times 10^{-3}$	$(1-45) \times 10^{-3}$	0		
B-Pb (umol/l)	195	$0,345 \times 10^{-3}$	$(0,04-2,9) \times 10^{-3}$	16	$1,084 \times 10^{-3}$	$(0,68-1,9) \times 10^{-3}$
B-ZPP umol/l	29	$0,470$	$0,02-3,3$	13	$0,210$	$0,08-0,68$
U-Cd nmol/l	139	$2,862 \times 10^{-3}$	$(0,2-24) \times 10^{-3}$	0		
U-Hg nmol/l	139	$6,094 \times 10^{-3}$	$(0,3-233) \times 10^{-3}$	0		
U-Kr mmol/l	153	$12,137 \times 10^{3}$	$(2,7-42) \times 10^{3}$	0		
	Collection of Hazardous Waste			**Treatment and disposal of Hazardous Waste**		
	N	**GM (umol/l)**	**Range (umol/l)**	**N**	**GM (umol/l)**	**Range (umol/l)**
B-Cd nmol/l	0			0		
B-Hg nmol/l	0			0		
B-Pb (umol/l)	16	$0,121 \times 10^{-3}$	$(0,04-0,29) \times 10^{-3}$	0		
B-ZPP umol/l	0			0		
U-Cd nmol/l	0			0		
U-Hg nmol/l	3	$1,194 \times 10^{-3}$	$(0,1-8,1) \times 10^{-3}$	17	$6,878 \times 10^{-3}$	$(3-38) \times 10^{-3}$
U-Kr mmol/l	3	$13,162 \times 10^{3}$	$(10-19) \times 10^{3}$	17	$14,978 \times 10^{3}$	$(8,2-32) \times 10^{3}$

6 CASE STUDIES

Most of the research that has been done is on measuring the exposure and not investigating effects for the workers in the formal recycling of WEEE.

The degree of hazard posed to the workers vary greatly with the specific methods used. In the following chapter several exposure studies is summarized to identify possible hazards for the workers working with recycling WEEE.

6.1 OCCUPATIONAL EXPOSURE TO METALS

6.1.1 *Case One*

In this study (Julander et al 2014, [49]) the workers exposure to elements was measured by using biomarkers and monitoring of personal air exposure. The exposure to 20 elements was assessed for 55 recycling workers and 10 office workers. The inhalable aerosol sub-fraction was collected using personal air samplers. To evaluate the biomarkers urine and blood samples were analysed.

The air samples showed a 10-30 times higher exposure to elements for the recycle workers than for the office workers. The biomarkers showed a significantly higher level of exposure for the recycling workers for chromium, cobalt, indium, lead and mercury in blood, urine and/or plasma than the office workers. The concentration of antimony, indium, lead, mercury and vanadium showed a linear relationship between the levels measured in blood, urine and plasma and the exposure levels measured in the inhalable aerosol sub-fraction.

The group with the greatest exposure to elements were the workers working with dismantling WEEE.

The correlation between the concentrations in the inhalable sub-fraction and the biomarkers, strongly indicate that the workers exposure to these elements is taking place at work. Their conclusion is that there is a need to also measure the exposure to rare metals like indium and antimony and not only the well-known contaminants mercury and lead.

6.1.1.1 *Indium*

Indium is mainly used in electronics as indium-tin oxide, mostly used in flat screens. The effect of exposure to indium is not well known with regards to its toxicity, but Indium phosphide is categorised as a probable carcinogens by the IARC and other indium compound are being investigated for their effect

[62]. The exposure was significantly higher for the dismantling workers than for any of the other groups. The proposed explanation for this is that indium-tin oxide is used as a thin film on displays, mostly LCD-screens, and it is only the dismantling workers that came in direct contact with either whole or dismantled screens. The workers exposure to indium is relevant since it is a component of flat screens, and this is a product that is increasingly recycled. There is some evidence that an exposure to indium at 3 μg/L in the blood can cause effects on the lung.

6.1.1.2 *Mercury and arsenic*

In this study only inhalable particles were collected because a considerable amount of the mercury will be present as vapour, the workers exposure to mercury is most likely underestimated. Even though, none of the workers worked with light bulbs containing mercury, the recycling workers had 20 times higher air exposure to mercury than the office workers. The probable source for the mercury is from back lights in different types of screens. The blood concentrations on the other hand did not show any significant difference. This is most likely caused by the fact that the main source for mercury in whole blood is through dietary exposure (methyl mercury).

The air measurements of arsenic did show a 23 times higher exposure for the recycling workers than the office workers.

Mercury and arsenic are commonly used in many types of electronics as LCDs and LEDs so the workers exposure to these elements will most likely only increase in the future.

6.1.1.3 *Lead*

Lead is predominantly found in the glass of cathode ray tubes and in solder and may be released when the lead containing WEEE is grinded. The grinded material where transported openly so it was possible for the lead containing particles to disperse and cause a lead exposure to all of the recycling workers, not only the ones working with dismantling. An exposure to lead is most serious for female workers since lead have been shown to affect an unborn child.

The process of grinding lead containing components have since been transferred to another company that specialises on treating lead containing components.

6.1.1.4 *Cadmium*

Cadmium is mostly present in batteries and printed circuit boards. The recycling workers had a 28 times higher air exposure to cadmium than the office workers. The cadmium concentrations in urine were as expected highest for the smokers. Among the non-smokers, the recycling workers had the highest urine concentration of cadmium. However, this difference is not statistically significant as most of the participants in the study were smokers.

6.1.2 *Case Two*

In 2008 and 2009 the National Institute for Occupational Safety and Health (NIOSH) were asked by the United States Department of Justice Office of the Inspector general to assist in the health and safety inspection of four UNICOR facilities recycling program at four Bureau of Prison institutions. The results from this assessment were published in the report "Exposure to hazardous metals during electronics recycling at four UNICOR facilities" [52].

The conclusion of this study was that UNICOR did not conduct adequate planning and job hazard analysis before the recycling work started. This lead to potential health hazards not being identified before they become relevant. No training were given to any of the workers, and adequate hazard controls were not implemented before after several years. In spite of this most of the workers had cadmium and lead levels in urine below the occupational exposure limit.

6.2 RECYCLING OF FLUORESCENT BULBS

There are several studies looking at the occupational exposure to mercury and other contaminants. The use of mercury in fluorescent bulbs is still permitted since the mercury is instrumental for the light bulb to function properly [51]

The amount of mercury differs greatly between different types of bulbs. A 120 cm long bulb contains approximately 12 mg of mercury [50]. In the mid-1980s a bulb could contain 40 mg or more mercury [50]. The average amount of mercury in fluorescent bulbs recycled is approximately 20 mg [50]. The bulbs will most likely break during conventional waste handling and thus release at least parts of the mercury which might cause occupational exposure to mercury. The amount of mercury released is a function of the form and amount of mercury, and external factors like temperature. Elemental mercury is used in the manufacturing of the bulbs. A certain amount of mercury vaporizes every time the bulb is used but condenses when the bulb cools [50]. After a time the elemental mercury is dispersed throughout of the bulb as small particles of beads that is too small to be seen with the naked eye [50]. This dispersion will increase the surface area of the mercury that will lead to an increased volatilization rate. Some of the mercury in the bulb will react with oxygen to solid mercury oxide (principally HgO) and some of the mercury will adhere to the glass as the bulb ages [50].

6.2.1 *Case Three*

To better know the fate of mercury in fluorescent bulbs an experiment was conducted by Aucott, McLinden and Winka [50]. The study mimicked a typical solid waste disposal scenario where the discarded bulbs break during handling before being stored in an open container for a time before it is disposed.

The concentrations measured in this study were well below the OEL for mercury. The results did show that the amount of mercury released is strongly dependent on temperature (figure 6). Figure 6 show the cumulated release of mercury from broken fluorescents over time at three different temperatures in percent of total mercury content. First an amount of available mercury is released, than after 8 hours the rate of emission decreases since the easily volatile mercury have been released or the Mercury is oxidized to solid mercury oxide. The results from this study can also be used to extrapolate the amount of mercury released from fluorescent bulbs to 2-4 tons of mercury each year in the United States of America.

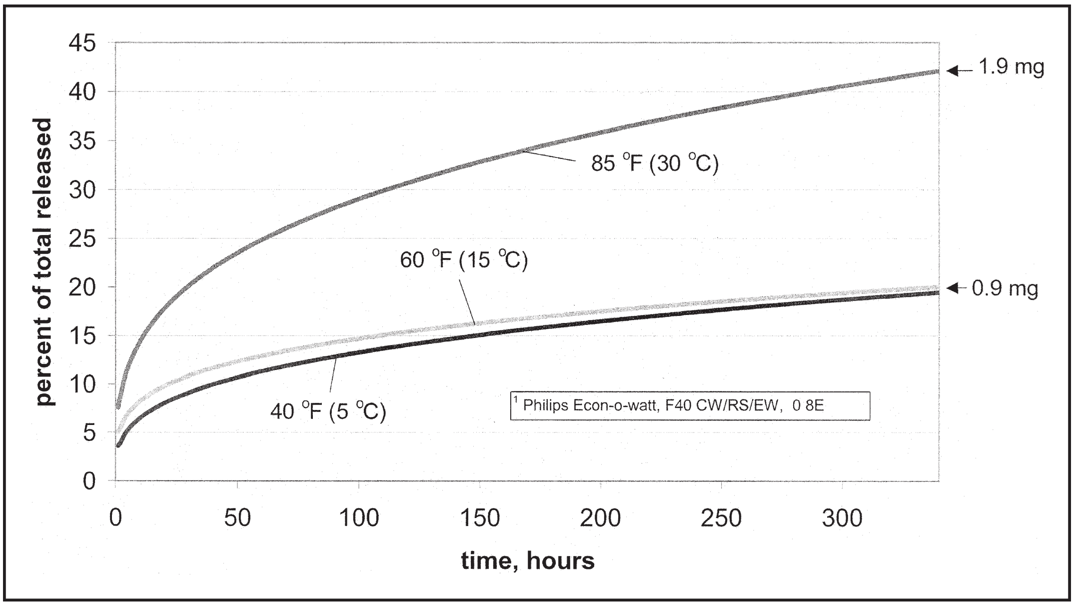


Figure 6: Cumulative release of mercury at three different temperatures as a function of time. Diagram copied from Aucott et al. 2003 [50].

6.2.2 *Case Four*

The purpose of the study conducted by Zimmermann et al. [51] was to determine the occupational exposure levels and the levels of emission of mercury in the different operations in the recycling of lamps in France.

Four facilities were inspected. The four different facilities had different procedures for recycling the lamps. Some of the facilities had pre-treatment existing of lamp storage and/or lamp sorting. The treatment used were either end cut or crushing (shredding). Some had storage of the output (glass, metal end parts etc.). The facilities did process different volumes ranging from 300 tons to 1600 tons.

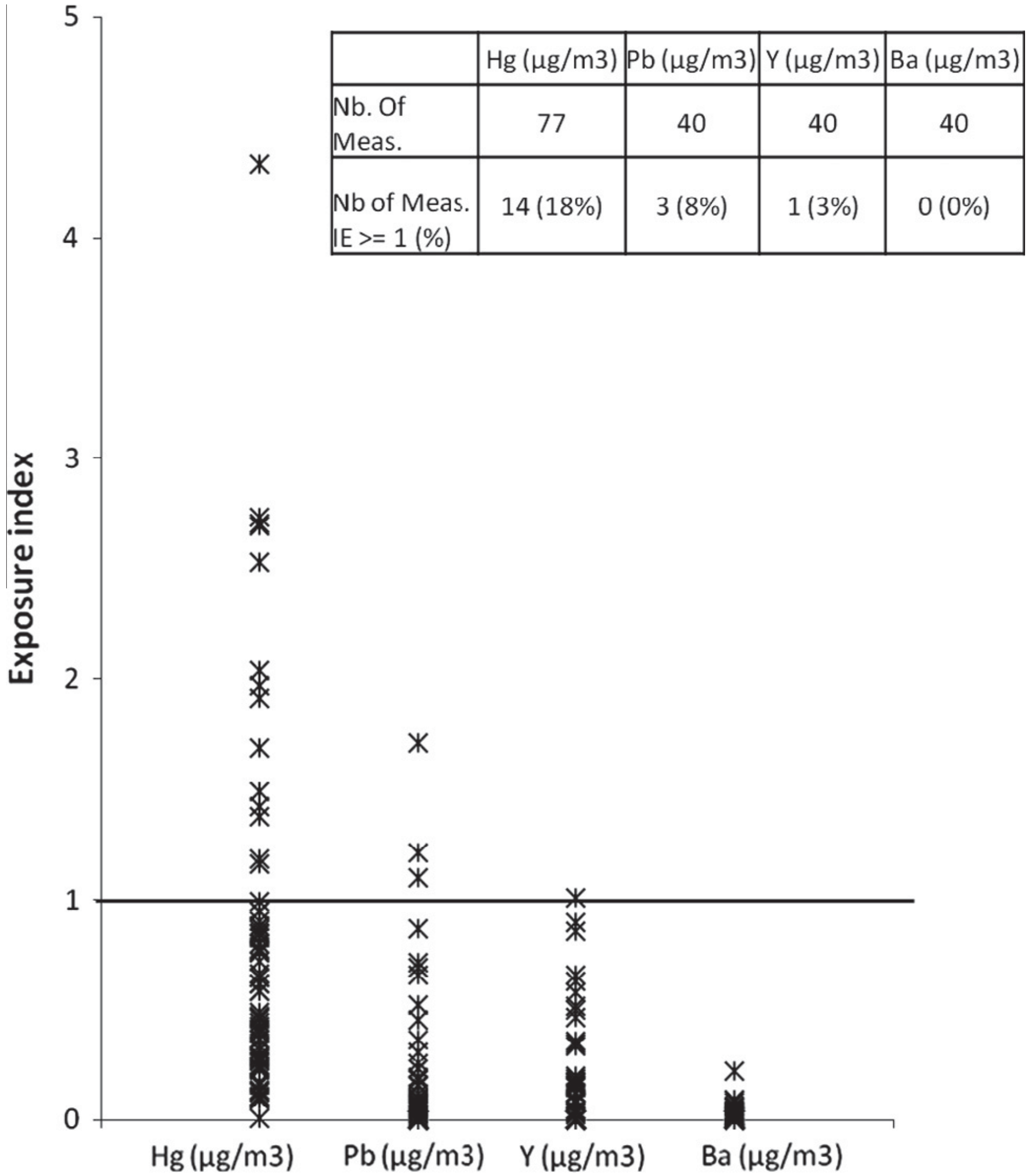
Lamp storage is where the loading and unloading operations take place. This area has low background concentrations of contaminants but peaks might appear if any light bulbs breaks. At lamp sorting there might be short time intervals where exposure might excess the OEL. Air concentrations up to 2430 $\mu g/m^3$ were measured for yttrium. The end cut process is enclosed in a low pressure confinement to avoid contaminating the surroundings. Still high concentrations were measured for inhalable dust, mercury and lead. The operators working with the crushing process were the group with the highest average exposure. The areas where the lamp input and output from the various treatment processes takes place are contaminated from the high volume of lamps that is broken during handling and feeding and this contamination leads to occupational exposure.

Figure 7 shows the individual measurements divided by the French OEL. The reason for this is to visualise the portion of measurements that exceeded the French OEL.

The study also analysed samples of dust from different surfaces. These measurements show an amount of barium, lead and yttrium. This shows the importance of good hand hygiene to avoid contaminating hands which then might cause ingestion to be a relevant route of exposure.

The study clearly shows that workers at all processes are exposed to what the authors calls worrying levels of mercury vapour and dust containing lead and yttrium. A list of appropriate measures to minimize the occupational exposure is also given. The list is (from Zimmerman et al. 2014 [51]):

1. Inputs and outputs should be stored and handling in ventilated areas. Broken lamps and outputs releasing mercury vapours should be confined in airtight containers.
2. Accidental breakages should be avoided by handling softly.
3. Existing processes should be improved by implementing source-capture methods and/or keep the core process in a vacuum confined enclosure.
4. Vacuum lock or a semi-automatic feed at the lamp input area should be implemented to keep the workers away from polluted area.
5. The mercury level should be continuously controlled at specific points in the workplace by real time measurement device connected with alarm system.
6. A general exhaust ventilation system should be implemented for all the workplace.



	Hg (µg/m3)	Pb (µg/m3)	Y (µg/m3)	Ba (µg/m3)
Nb. Of Meas.	77	40	40	40
Nb of Meas. IE >= 1 (%)	14 (18%)	3 (8%)	1 (3%)	0 (0%)

Figure 7: Atmospheric measurements of mercury, lead, yttrium and barium divided by France OELs. Copied from Zimmermann et al. 2014 [51].

7. In addition to prevention by source reduction and collective protection, suitable personal protective equipment may be required especially for limited and hazardous activities (e.g. cleaning and maintenance operations). Finally, good conditions of hygiene should be ensured (e.g. hand washing before break, shower and clothe changing at the end of workday, working clothes supplied and washed by company).

6.3 BROMINATED FLAME RETARDANTS

There have been several studies assessing workers exposure to brominated flame-retardants.

6.3.1 *Case Five*

The Department of Work Environment Development at the Finnish Institute of Occupational Health published a study in 2011 [56] on the exposure of workers at four different recycling sites to BFR.

In this study the airborne concentrations in breathing zone of five flame retardants were measured. The five compounds where: tetrabromobisphenol-A (TBBP-A), decabromodiphenylethane (DBDPE), hexabromocyclododecane, 1,2-bis(2,4,6-tribromophenoxy)-ethane, hexabromobenzene, and one chlorinated flame retardant (Dechlorane Plus®). In addition to these polybrominated diphenylethers and polybrominated biphenyls were measured. The air concentrations were measured at four different plants, over a period of two years.

The study found that the three most abundant of the measured compounds were PBDEs (mostly deca-BDE) 21 to 2320 ng/m^3, TBBP-A 8,7 to 430 ng/m^3, and DBDPE 3,5-360 ng/m^3. At two of the sites there were a decrease of exposure that correlated with the emission control actions (improved ventilations, improved maintenance of ventilation and improvements of the cleaning procedures). The decrease of exposure was between 10-68 % and 14-79 % in the two facilities. When assessing if the measured concentrations could cause adverse health effects for the workers, the researchers had some problems caused by the lack of OEL for the flame retardants. There is no OEL in Finland for any of the compounds in this study. Since these compounds are suspected endocrine disruptors there is a possibility for antagonistic effects where even low levels might cause an effect. Since the study shows that the occupational exposure might be decreased by preventive measures one should strive to minimize the exposure by keeping the levels as low as reasonably practicable.

6.3.2 *Case Six*

Flame retardants exposure: PBDEs in blood from Swedish workers This study was published in 1999 (Sjödin et al. 1999) where the blood serum levels of five PBDE congeners, 2,2′,4,4′-tetraBDE; 2,2′,4,4′,5,5′-hexaBDE; 2,2′,4,4′,5,6′-hexBDEE; 2,2′,3,4,4′,5′,6-heptaBDE; and decaBDE were measured. The workers studied were clerks working full time with a computer and workers at a dismantling site for WEEE. Hospital cleaners were used as a control group.

This study found that the subjects working with dismantling electronics had significantly higher levels of all of the studied PBDEs. The compound found in the highest concentrations in the dismantling workers was 2,2′,3,4,4t,5′,6-heptaBDE. The total amount of all the congeners in the serum was 37 pmol/g lipid weight for the dismantling workers, 7, 3 pmol/g lipid weight for the office workers and 5, 4 pmol/g lipid weight for the hospital cleaners. The conclusion of this study is that decabromodiphenyl ether is bioavailable and that the workers at the WEEE dismantling site where occupationally exposed to these compounds. This conclusion is supported by the data from the change in PBDE levels in 11 workers before and after they went for vacation. They also found that the different compounds seemed to have a different half-life inversely proportional to the degree of bromination, the more brominated the compound the shorter half-life.

6.3.3 *Case Seven*

In another paper from Sweden published in 2001 [58], the hypothesis is that the polybrominated flame-retardants were released during the dismantling process of WEEE and that there is a possibility that these compounds pose an occupational health hazard. The air from different working environments were examined: a recycling plant, a factory assembling printed circuit boards, a computer repair facility, an office and outdoor air.

This study found polybrominated diphenylethers, polybrominated biphenyls, 1,2-bis(2,4,6-tribromophenoxy)-ethane, tetrabromobisphenol A, and organophosphate esters in all of the air samples. The highest concentrations were measured in the air from the recycling plant. In the recycling plant the air was sampled from two different locations, the dismantling hall and by the shredder. The air sample from the dismantling hall showed decabromodiphenyl ether at 38 $pmol/m^3$, tetrabromobisphenol A at 55 $pmol/m^3$, and triphenylphosphate at 58 $pmol/m^3$. By the shredder it was measured significantly higher levels of all of these compounds and this was the first time it is shown occupational exposure to 1,2-bis(2,4,6-tribromophenoxy)-ethane and several arylated phosphate esters.

The conclusion of this study is that brominated and phosphorus-containing additives to plastic materials is released to the air in the process of recycling WEEE.

6.3.4 *Case Eight -A follow up to Case Seven*

A further study of the occupational exposure of workers in the recycling of WEEE industry to polybrominated diphenylether was published in 2006 [59]. After the studies conducted by Sjödin et al. 1999 [57] and Sjödin et al. 2001 [58] the factory decided to implement industrial hygienic measures to decrease the exposure. The effectiveness of these measures to decrease the levels of PBDEs in the blood serum of the workers was analysed in this study.

In the time between the sampling in the first study (1997) and the second sampling (2000) there was implemented significant changes. The schematic changes to the factory layout is shown in figure 8. Since it was identified that the shredder where the primary source for releasing PBDE [58] the shredder where moved outside the factory. In 1997 the factory did not have any ventilation, but this was improved by installing a specific process-ventilation system that forced the airflow from ceiling to the floor to remove the dust particles in the air. The cleaning routines were improved by installing an industrial vacuum cleaner operating on wet floor in addition to sweeping all workstations and benches with wet rags. It is also important to note that the volume of dismantled and recycled electronics increased greatly, the volume was doubled between 1997 and 2000 from 1900 tons to 38000 tons. Of this, 75 tons in 1997 were plastic containing BFR compared to 195 tons in 2000.

This study found decrease in BDE-47, BDE-183 and BDE-209. It is hypothesised that the difference in the reduction between different brominated flame-retardants can be explained by the difference in half-life between the compounds. The low-medium brominated PBDEs did not have the same reductions as the more brominated PBDEs.

These improvements were achieved even though the processes volume doubled between the measurements were taken and analysed.

The conclusion is that occupational exposure to brominated flame-retardant can be decreased through structural process planning, good ventilation and good cleaning procedures.

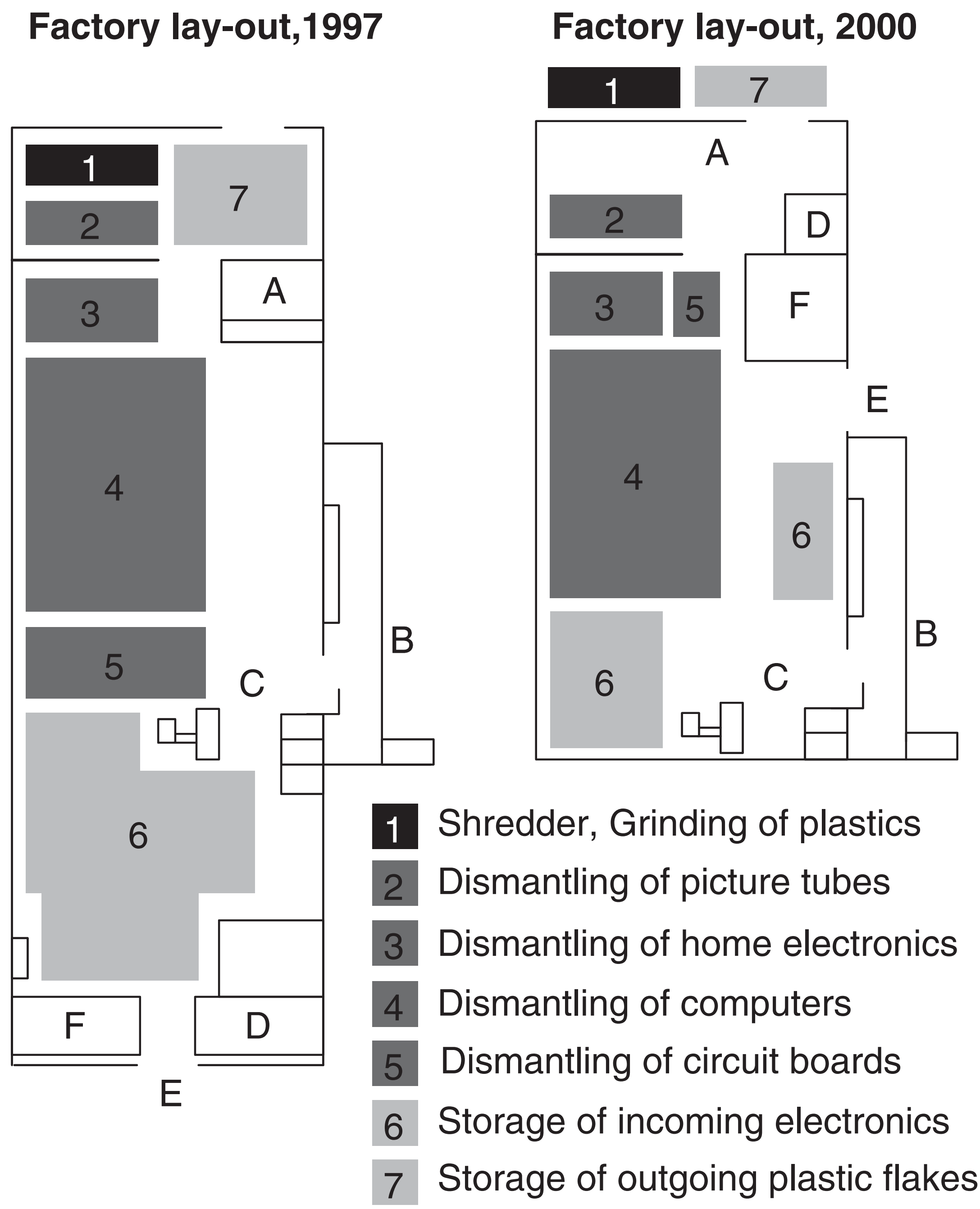


Figure 8: The factory lay-out before and after the factory implemented measures to minimize the levels of BRFs in the work environment. Copied from Thuresson et al. 2006 [59].

7

SITUATION IN NORWAY

Norway is the country in the world with the highest generation of WEEE [5]. This increase in waste generation does not necessarily constitute an increased environmental or human health problem since Norway also returned the most WEEE for proper treatment [63]. As with the rest of the world Norway is best at properly disposing the big EEE like washing machines and television sets but is not so good at returning small EEE like mobile phones and light bulbs [3, 5, 63].

The three most environmentally hazardous waste fractions are WEEE (mercury containing electronic equipment, mercury containing light bulbs, plastic from WEEE that contain BFR) [16].

A simplified model of the life cycle and management and recycling of EEE in Norway is shown in figure 9.

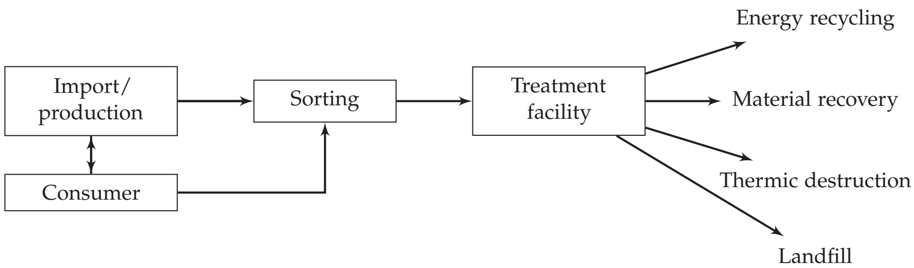


Figure 9: A schematic model of the management and recycling of WEEE in Norway. After collection of the WEEE either from the consumer or the importer/producer the WEEE undergoes at least one manual sorting process before it is shipped to a treatment facility. There the WEEE is (manually) dismantled and the components undergo either energy recycling, material recovery, thermic destruction or is shipped to a landfill.

7.1 LEGISLATION

Recycling in Norway is regulated through the "Forskrift om gjenvinning og behandling av avfall" (Regulations about Recycling and Treatment of Waste) called "avfallsforskriften" (Waste Regulations) [4]. The Norwegian waste regulation has been adapted to implement the European WEEE-directive from 2006, and the environmental authority are working on some suggested changes to the waste regulation to implement the changes in the WEEE-directive from 2014 [64].

The legislation that is relevant for the recycling of waste electrical and electronic equipment is chapter 1 "Kasserte elektriske og elektroniske produkter" (Waste electrical and electronic equipment) [4].

This regulates all receiving, collection of, recycling and all other treatment of waste electrical and electronic equipment except batteries. All treatment of waste batteries are regulated through chapter 3 "Kasserte batterier" (waste batteries) [65].

The goal of the regulation of the treatment of WEEE is to reduce the environmental impact of discarding electrical or electronic equipment when considering the environment, use of resources and economic factors [4]. The impact is reduced by separate collection, sorting and treatment of the parts that is considered hazardous waste and to achieve the greatest possible degree of recycling of the rest of the WEEE [4].

7.2 ORGANISATION OF WEEE HANDLING IN NORWAY

All vendors that sell EEE are obligated to receive WEEE [66]. This applies even if the costumer does not buy any new products, and the product returned is independent of manufacturer and model, it only needs to be an equivalent product. After receiving these products the vendors are required to handle and store the products in a way that minimize damage to the product, to minimize unwanted emissions, until the WEEE is collected by the return company.

In Norway, the collection and treatment of WEEE is founded through a fee on all import electronics to Norway. This fee has to be paid to a certified return company. The return companies are responsible to administrate the management and recycling of WEEE. They does not do any of the collection or treatment of the recycled products but they employ contractors. A result of this producer responsibility means that the return companies have to evaluate the hazardous content in both old and new product, and even though the new product is more environmentally friendly it is the fee on the new product that is financing the management and recycling of the old products.

The return companies is required to submit a wide set of data either on an annual or biannually on basis. These statistics are managed by eeregisteret.no.

The return companies have to supply data about:

- Export of EE-products
- Collected EE-products sorted by county, municipality and product group
- Total supply of new EEE and total collected WEEE
- Amount of recycling sorted by product group
- Treated materials per waste groups
- Treated WEEE sorted by product group and type of treatment

The following tables (table 5-9) describe the treatment of WEEE generated in Norway, with how the different product groups end up, and amount of the treatment done in Norway and abroad.

These tables show that most of the WEEE returned in Norway are treated in Norway. After the WEEE have been returned the WEEE is collected by contractors and then first sorted into nine different fractions[67] [68]. These fractions are than sent to different treatment facilities where they either are sorted further into several more fractions or directly to be treated [67][68]. The treatments used further follow the international trends and as described in Chapter 3. So even if the WEEE is treated abroad, it goes through at least one manual sorting process in Norway.

A challenge in the dismantling process is about how they identify the hazardous components. This selection process is based on the treatment facilities knowledge and experience [68]. A good example is how Renas handled the return of the smart current meters [68]. Renas asked their contractors to collect one of each kind of these smart current meters, and these were then analysed to identify hazardous components that need to be removed[68].

Norsk Gjenvinning mentioned that in their sorting operation the chemical hazards were evaluated to be of low risk [67]. The highest rated risk were the mechanical and physical hazards [67]. The personal protection equipment that were used at all times were protective footwear and gloves and breathing masks were available if the workers found the need to use them [67].

Table 5: Report on achieved total levels of recycling, material recovery and reuse compared to the govermental demands in 2013. All return companies [64]

	Requirement		Actual levels	
	Level of recycling (%)	**Level of material recycling and re-use (%)**	**Level of recycling (%)**	**Level of material recycling and re-use (%)**
Total			**93,9**	**82,1**
1. Big home appliances	80	75	94,1	79,3
1a. Refrigeration systems	80	75	98,3	84,9
1b.Other house appliences	80	75	91,8	76,2
2. Small home appliances	70	50	96,8	83,6
3. Data treatment-, telecomunication -, and office appliances	75	65	95,1	82,1
3a. Computer monitor	75	65	95,2	82,3
3b. Other data treatment-, telecomunication -, and office appliances	75	65	95,1	82,1
4. Sound and picture appliances	75	65	94,6	80,4
4a. Television	75	65	93,3	77,9
4b. Other sound and picture appliances	75	65	96,3	83,8
5. Lighting appliances	70	50	94,8	85,4
6. Lightsources		80	93,2	91,3
7. Electric and electronic tools	70	50	94,4	87,4
8. Toys, Leker, leisure and sports appliances	70	50	97,1	84,3
9. Medical equipment			94,9	81,3
10. Surveillance and controll appliances	70	50	95,2	83,9
10a. Smoke detectors	70	50	74,9	63,8
10b. Other surveillance and controll appliances	70	50	95,4	84,1
11. Automatic vendor machine	80	75	98,5	87,1
12. Cables and wires			87,1	75,9
13. Electro technic equipment			96,3	90,2
14. Heating equipment, air conditioning and ventilation			94,9	85,0

Table 6: Report from all five return companies of total amount of WEEE from Norway treated in all countries in 2013, by treatment and product group [64]

Product group/ Treatment	**Treated total**	**Other treat-ment**	**Landfilling**	**Energy recyled**	**Material recycled**	**Thermal destruc-tion**
Total	**144 788,6**	**409,6**	**8 151,3**	**17 091,8**	**118 908,4**	**227,5**
1. Big home appliances	**45 460,5**	239,4	2 373,7	6 724,1	36 058,7	64,6
1a. Refrigeration systems	**16 215,0**	161,1	61,1	2 168,4	13 768,0	56,4
1b.Other house appliences	**29 245,5**	78,3	2 312,6	4 555,7	22 290,6	8,2
2. Small home appliances	**5 429,1**	0	157,3	716,0	4 541,2	14,5
3. Data treatment-, telecomunication -, and office appliances	**13 144,7**	51,2	568,9	1 703,1	10 795,4	26,1
3a. Computer monitor	**1 827,4**	0,1	87,6	235,2	1 503,8	0,6
3b. Other data treatment-, telecomu-nication -, and office appliances	**11 317,3**	51,1	481,3	1 467,9	9 291,6	25,5
4. Sound and picture appliances	**16 256,9**	98,8	762,8	2 306,2	13 074,3	14,7
4a. Television	**9 326,4**	79,9	533,4	1 441,4	7 263,8	8,0
4b. Other sound and picture appli-ances	**6 930,5**	18,9	229,4	864,8	5 810,5	6,8
5. Lighting appliances	**8 884,2**	6,2	449,1	828,7	7 590,2	10,0
6. Lightsources	**903,8**	0	61,1	17,3	825,2	0,2
7. Electric and electronic tools	**9 895,7**	0	553,6	688,0	8 651,5	2,6
8. Toys, Leker, leisure and sports ap-pliances	**669,0**	0	19,3	85,1	564,3	0,3
9. Medical equipment	**524,6**	0	25,6	71,3	426,4	1,4
10. Surveillance and controll appli-ances	**2 138,6**	0	100,5	242,2	1 793,9	1,9
10a. Smoke detectors	**23,2**	0	5,8	2,6	14,8	0,1
10b. Other surveillance and controll appliances	**2 115,4**	0	94,7	239,6	1 779,1	1,9
11. Automatic vendor machine	**469,7**	0	5,7	53,5	409,2	1,4
12. Cables and wires	**16 964,4**	0,6	2 135,6	1 896,3	12 881,9	50,0
13. Electro technic equipment	**16 651,8**	6,2	577,4	1 023,2	15 012,5	32,5
14. Heating equipment, air condi-tioning and ventilation	**7 395,5**	7,2	360,7	736,7	6 283,7	7,3

Table 7: Report from all five return companies of total amount of WEEE treated in Norway in 2013, by treatment and product group [64]

Product group/ Treatment	Treated total	Other treat-ment	Landfilling	Energy recyled	Material recycled	Thermal destruc-tion
Total	**83 990,6**	**161,8**	**5 152,0**	**7 211,7**	**71 390,2**	**74,9**
1. Big home appliances	**29 638,8**	74,9	2 251,7	2 863,7	24 439,3	9,2
1a. Refrigeration systems	**6 124,5**	0	52,7	1 517,6	4 546,5	7,7
1b.Other house appliences	**23 514,3**	74,9	2 199,0	1 346,1	19 892,8	1,5
2. Small home appliances	**1 939,6**	0	56,6	200,6	1 682,0	0,4
3. Data treatment-, telecomunication -, and office appliances	**3 976,6**	0	177,4	364,8	3 419,9	14,5
3a. Computer monitor	**218,0**	0	11,0	23,9	182,9	0,3
3b. Other data treatment-, telecomu-nication -, and office appliances	**3 758,5**	0	166,4	341,0	3 237,0	14,2
4. Sound and picture appliances	**2 831,7**	79,2	119,0	201,0	2 423,3	9,2
4a. Television	**1 126,1**	79,2	57,8	79,1	902,4	7,6
4b. Other sound and picture appli-ances	**1 705,6**	0	61,2	121,9	1 521,0	1,5
5. Lighting appliances	**7 100,1**	0	384,4	600,5	6 110,1	5,2
6. Lightsources	**0,3**	0	0	0	0,3	0
7. Electric and electronic tools	**8 653,1**	0	513,0	545,9	7 592,3	1,8
8. Toys, Leker, leisure and sports ap-pliances	**265,1**	0	8,9	40,5	215,5	0,2
9. Medical equipment	**365,8**	0	20,6	57,3	286,9	0,9
10. Surveillance and controll appli-ances	**1 950,9**	0	97,2	197,5	1 654,6	1,5
10a. Smoke detectors	**22,1**	0	5,7	2,5	13,9	0
10b. Other surveillance and controll appliances	**1 928,8**	0	91,5	195,0	1 640,8	1,5
11. Automatic vendor machine	**197,4**	0	4,2	42,8	149,7	0,8
12. Cables and wires	**5 748,0**	0,6	648,6	762,2	4 336,5	0
13. Electro technic equipment	**15 322,4**	0	544,1	856,0	13 891,3	31,0
14. Heating equipment, air condi-tioning and ventilation	**6 000,8**	7,0	326,2	478,9	5 188,6	0,1

Table 8: Report from all five return companies of total amount of WEEE from Norway treated abroad in 2013, by treatment and product group [64]

Product group/ Treatment	**Treated total**	**Other treat-ment**	**Landfilling**	**Energy recyled**	**Material recycled**	**Thermal destruc-tion**
Total	**60 798,0**	**247,8**	**2 999,3**	**9 880,1**	**47 518,3**	**152,6**
1. Big home appliances	**15 821,8**	164,5	122,0	3 860,5	11 619,4	55,5
1a. Refrigeration systems	**10 090,6**	161,1	8,4	650,8	9 221,6	48,7
1b.Other house appliences	**5 731,2**	3,4	113,6	3 209,7	2 397,8	6,8
2. Small home appliances	**3 489,5**	0	100,6	515,4	2 859,3	14,1
3. Data treatment-, telecomunication -, and office appliances	**9 168,1**	51,2	391,6	1 338,3	7 375,5	11,6
3a. Computer monitor	**1 609,3**	0,1	76,6	211,4	1 320,9	0,3
3b. Other data treatment-, telecomu-nication -, and office appliances	**7 558,8**	51,1	314,9	1 126,9	6 054,6	11,3
4. Sound and picture appliances	**13 425,2**	19,6	643,8	2 105,2	10 651,0	5,6
4a. Television	**8 200,4**	0,7	475,6	1 362,3	6 361,4	0,3
4b. Other sound and picture appli-ances	**5 224,8**	18,9	168,2	742,9	4 289,6	5,2
5. Lighting appliances	**1 784,1**	6,2	64,7	228,2	1 480,1	4,7
6. Lightsources	**903,5**	0	61,1	17,3	824,9	0,2
7. Electric and electronic tools	**1 242,7**	0	40,6	142,0	1 059,2	0,8
8. Toys, Leker, leisure and sports ap-pliances	**403,9**	0	10,4	44,6	348,8	0,1
9. Medical equipment	**158,8**	0	4,9	13,9	139,5	0,5
10. Surveillance and controll appli-ances	**187,7**	0	3,3	44,7	139,3	0,4
10a. Smoke detectors	**1,1**	0	0	0,1	0,9	0,1
10b. Other surveillance and controll appliances	**186,5**	0	3,2	44,6	138,4	0,3
11. Automatic vendor machine	**272,3**	0	1,5	10,7	259,5	0,6
12. Cables and wires	**11 216,3**	0	1 487,0	1 134,0	8 545,4	50,0
13. Electro technic equipment	**1 329,4**	6,2	33,3	167,2	1 121,2	1,4
14. Heating equipment, air condi-tioning and ventilation	**1 394,7**	0,1	34,5	257,9	1 095,1	7,1

Table 9: Report from all five return companies with the treatment and amount of different components and materials in all countries from 2013 [64]

Materials/ Type of waste / Treatment	Treated total	Other treat-ment	Landfilling	Energy recyled	Material recycled	Thermal destruc-tion
All products group total	**113 476,7**	**74,0**	**7 366,7**	**15 742,8**	**89 923,4**	**369,7**
a. Capasitors and/or other components that contain PCB or PCT.	**42,0**	0	0,2	13,0	0,2	28,6
b. Capatisors with height/width/diameter above 25 mm that contain environmental pollutions (except from above mentioned in a.)	**148,8**	0	0	0,4	0	148,3
c. Toner cartridges	**132,5**	56,8	0	69,9	0	5,8
d. External batteries. All batteries tkat is possible to remove without specialiced tools and internal batteries that is hazardous waste. Except batteries mounted on printed circuit board.	**626,4**	0	33,7	142,3	450,3	0
e. Other batteries than mentioned in d.	**74,9**	0	0,6	9,0	65,3	0
f. Asbestos and asbestos containing components.	**37,6**	0	37,6	0	0	0
g. Fireproof ceramic fibre	**4,9**	0	4,9	0	0	0
h. Mercury containing LCD backlights	**4,0**	0	4,0	0	0	0
i. LCD screens above 100 cm2. All LCD screens with fluorescent tubes backlight	**858,8**	2,9	27,7	64,0	764,2	0
j. Other mercury containing components	**24,5**	0	24,5	0	0	0
k. Cathode ray tubes including fluorescent coating	**8 128,4**	0	398,7	1 263,8	6 465,9	0
l. Printed circuit board	**2 543,2**	0	4,6	708,4	1 808,1	22,0
m. Chlorfluorcarboner (CFC),	**77,6**	3,8	1,4	13,4	0,7	58,3
n. SF6-gas	**0,9**	0,9	0	0	0	0
o. Beryllium, exept from beryllium in components on printed circuit board	**0,7**	0	0,7	0	0	0
p. Plastic containing BFR	**2 335,6**	0	3,6	2 309,1	12,4	10,4
q. External electrical cables	**15 483,3**	0	2 039,4	1 190,2	12 204,3	49,4
r. Components in WEEE that contain radioactive sources, like smoke detector	**12,9**	0	5,8	1,0	6,1	0
s. Waste sontaining oil, including waste oil	**841,6**	9,7	1,2	792,2	15,7	22,9
t. Gas-discharge lamp -fluorecent tube	**689,7**	0	41,0	0	648,1	0,7
u. Gas-discharge lamp light bulb	**239,4**	0	14,3	0,1	224,9	0,1
v. Other hazardous waste	**130,7**	0	12,7	111,2	4,9	1,8
w. Environmental remediated WEEE to be shredded	**81 038,4**	0	4 710,0	9 054,6	67 252,3	21,5

8 DISCUSSION

WEEE is the fastest growing waste stream. It is well known that EEE contains compounds and components that are hazardous both for man and the environment. These components must be safely removed to minimize the negative impact of this waste and it is good resource management to preserve as much as possible of the valuable content.

This industry relies primarily on manual sorting and dismantling. In the process of managing this waste stream there is a potential for occupational exposure to several different hazardous compounds.

In 2013, 140 000 tons of WEEE was collected in Norway. All of this went through at least one manual sorting process. Of the total collected volume of WEEE, 80 000 were treated and recycled in Norway. The WEEE recycling industry in Norway follow international trends, and it is more than likely that the information from the recycling in other industrialised countries are representative for the situation in Norway. Generally, the studies on the formal recycling of WEEE show that there are a potential for occupational exposure to a range of inorganic and organic compounds. The international studies identified several compounds at elevated concentrations but the geometric mean concentrations in the formal recycling where found to be generally below the relevant OELs. The work operation where all the different studies found the highest levels of exposure were the dismantling process. Dismantling is extra relevant since it is a manual process that is hard to automate caused by the heterogeneity of the WEEE. An additional challenge connected to the dismantling process are importance of extracting as much as possible of the hazardous substances. Remaining substances might be released to the work environments in later processing, like shredding. A couple of studies did identify the shredders as significant point sources for releasing hazardous compounds into the work environment. The lack of removal of hazardous substances might be caused by missing knowledge about the placement of hazardous components or the ghost effect where hazardous substances are found in supposedly clean materials and components.

The main substances that have been described in the international studies are several elements (for example lead, cadmium, mercury, indium, arsenic, yttrium, barium etc) and several BFRs and some dioxins. The international studies shows single measurements that exceed the OELs but as mentioned the geometric means were below the relevant OELs. The fact that these substances were identified in the chemical work environment show that exposure is taking place and it should be considered to measured these substances alongside the well-known contaminants like lead, cadmium and mercury.

A problem specifically mentioned in Case Five were the problems in evaluating the effects of the concentrations of BFRs since the scientists lacked any OELs to use in their calculations. Another challenge with evaluating the adverse health effect of exposure to BFRs are the fact that these substances are endocrine disruptors and the exposure of several different endocrine disruptors might cause either synergistic or antagonistic effects.

There are also additional substances that several reports mention as potential problems but that have not been further studied in formal recycling. These substances are constituents of plastic, bisphenol A, PFRs, and phtalates. Another group of substances that have had little attention in the international literature but will have an increasing relevance are the compounds use to make LCD-screens. The use of LCDs are rapidly increasing and are already found in everything from coffee-makers to printers, TVs, mobile phones and computer screens and the amount of the LC that need to be treated is increasing. At the moment there have only been identified some LC that are considered to be irritating, corrosive or sensitising to the skin but further studies are being done to evaluate other possible adverse health effects. Another hazardous compound of interest in the LCD is indium. Another relevant product that is expected to be increasingly recycled in the coming years are mercury containing light bulbs. Case Four shows that it will also be relevant to measure other elements used in fluorescent bulbs other than mercury, such as lead, yttrium and barium.

These is a general knowledge gap with concern to the composition of the chemical work environment in the management and recycling of WEEE in Norway. The available data from Norway shows low concentrations of the measured elements and solvents in the work environments. But the available information is scarce with few measurements spread over several different facilities, processes and years. There are a complete lack of data from Norway regarding organic compounds found in WEEE-plastic: BFRs, PCB, PFCs, bisphenol A, phthalates or compounds that might be created in thermal processes like the speciation of the inorganic particles or dioxins.

A couple international studies did show that preventive measures can have a huge positive effect, for instance in Case Seven and Case Eight. They found that much of the BFRs were released as particles, and by improving the ventilation, separating the shredder from the rest of the processes and generally improving their cleaning routines they achieved a decrease in the workers exposure to BFRs even though the volume of BFR containing plastic had more than doubled in the same period. These measures would most likely also have a positive impact on the concentrations of other substances in the work environment since most of the substances would be present as particles.

9

CONCLUSION

All of the 140 000 tons of collected WEEE in Norway goes through at least one manual sorting process, and 80 000 tons of the WEEE are treated in Norway. The chemical work environment in this industry is highly relevant to characterize since several of the processes (sorting, dismantling) are dependent on manual labour.

The available data about the chemical work environment in this industry are scarce. There are some data about the concentrations of some organic solvents in air and some data about the concentrations of inorganic elements in biological samples and in air samples. This data shows low levels of exposure, but the measurements are split over different companies, processes and years. The international data also show relativly low concentrations of hazardous compounds, but they also identifies several compounds that are of interest to measure in the recycling industry in Norway. The available data is not enough to conclude about the state of the chemical work environment in the managing and recycling of WEEE in Norway. There is a need for further data with a better resolution on the different processes and substances.

Some studies did show a considerable improvement to the chemical work environment through implementing better ventilation, separation of work processes and thorough cleaning.

There is a potential for occupational exposure to a wide range of hazardous substances when working with managing and recycling of WEEE. This exposure is possible to minimize through implementing preventive measures. The available data indicate low concentrations of the hazardous substances in the work environment but further studies are needed to evaluate the state of the chemical work environments where they manage or recycle WEEE in Norway.

A

INTERVIEW QUESTIONS

A.1 RENAS

- Kort fortelle om resirkulering av WEEE i Norge og hvilke posisjon Renas fyller?
- Hvordan blir WEEE behandlet i Norge?
- Hva blir gjort i Norge og hva blir eksportert?
- Hva avgjør hvor WEEE blir bearbeidet? Hvilke kriterier benytter dere når dere organiserer/planlegger?
- Hvordan forventer dere at dere/industrien vil håndtere økningen i E-avfall i årene som kommer? (Økt mengde bearbeidet i Norge/Økt mengde eksportert ut)
- Hvilke stoffer fokuserer dere på? (Noen utover listen på nettet?)
- Benyttes det mest manuell eller mer automatiserte dissmantling prosesser?
- Hvor effektiv er dissmantling delen av prosessen? Blir tilstrekkelige mengder av de verdifulle og de farlige komponentene fjernet?
- Gå kjapt igjennom data levert av EEregisteret for 2013, spesielt fokus på «Behandlete materialtyper/avfallsfraksjoner. 2013». (Hvorfor er det en større mengde oppgitt når en ser på produktgrupper sammenlignet med materialtype/avfallsfraksjon?)
- Hvordan fordeler de ulike operasjonene seg mellom land? (Demontert i et land, behandlet i et annet/Alt i samme land)
- Har dere noen prognoser for hvordan type/fordeling av WEEE vil endre seg med tiden? (Nye store produktgrupper som kommer/Nye farlige eller verdifulle komponenter)
- Hvordan ser dere på dagens rapporteringskrav?
- Tar dere noen stilling til arbeidsmiljøet hos deres kontraktører?
- Hva er grunnen for at det bare er Elsirk som ombrukte WEEE i 2013? Er det de eneste som får inn WEEE som kan brukes igjen eller eneste som har kontakt med den spesifikke underleverandøren?
- Setter dere krav til oppbevaring av WEEE før det blir innsamlet av dere? Åpen/lukket beholder / Tidsaspekter

A.2 NORSK GJENVINNING

- Hvordan blir WEEE behandlet hos dere?
- Hvordan er logistikken rundt WEEE hos dere? (Hvor får dere WEEE fra? Eventuelt sorterer dere? Noe som blir delvis behandlet så sendt videre?)
- Hva avgjør hvor WEEE blir bearbeidet? Hvilke kriterier benytter dere når dere organiserer/planlegger?
- Hvordan forventer dere at dere/industrien vil håndtere økningen i E-avfall i årene som kommer? (Økt mengde bearbeidet i Norge/Økt mengde eksportert ut)
- Hvilke stoffer som kan være skadelig i arbeidsmiljøet fokuserer dere på?
- Hvilke tiltak har dere igangsatt for å ha kontroll på og bedre det kjemiske arbeidsmiljøet?

[1] Miljødirektoratet, "Miljøstatus i Norge : Elektrisk og elektronisk avfall," June 2013.

[2] Eurostat, "Waste Electrical and Electronic Equipment (WEEE) - Eurostat," 2015.

[3] K. Lundgren, "The global impact of e-waste Addressing the challenge," 2012.

[4] Lovdata, "Lovdata - Forskrift om gjenvinning og behandling av avfall (avfallsforskriften) - Kapittel 1. Kasserte elektriske og elektroniske produkter," June 2006.

[5] K. Balde, F. Wang, R. Kuehr, and J. Huisman, "THE GLOBAL E-WASTE MONITOR 2014," 2015.

[6] M. Mergel, "Green Chemistry - Toxipedia," Nov. 2010.

[7] J. Cui and E. Forssberg, "Mechanical recycling of waste electric and electronic equipment: a review," *Journal of Hazardous Materials*, vol. 99, pp. 243–263, May 2003.

[8] I. R. Kielland and K. Larssen, "Farlige forbindelser - DN.no," May 2014.

[9] NRK, "FN advarer mot giftig e-søppel - Nyheter, tv og radio fra hele verden - NRK.no," Feb. 2015.

[10] Dagbladet, "Nordmenn kaster mest elektronisk avfall i verden - nyheter - Dagbladet.no," Apr. 2015.

[11] O. Tsydenova and M. Bengtsson, "Chemical hazards associated with treatment of waste electrical and electronic equipment," *Waste Management*, vol. 31, pp. 45–58, Jan. 2011.

[12] K. Grant, F. C. Goldizen, P. D. Sly, M.-N. Brune, M. Neira, M. van den Berg, and R. E. Norman, "Health consequences of exposure to e-waste: a systematic review," *The Lancet Global Health*, vol. 1, pp. e350–e361, Dec. 2013.

[13] Norsk Gjenvinning, "Gjenvinning av metall," 2015.

[14] T. Matsuto, C. H. Jung, and N. Tanaka, "Material and heavy metal balance in a recycling facility for home electrical appliances," *Waste Management*, vol. 24, no. 5, pp. 425–436, 2004.

[15] J. Cui and L. Zhang, "Metallurgical recovery of metals from electronic waste: A review," *Journal of Hazardous Materials*, vol. 158, pp. 228–256, Oct. 2008.

[16] Norges Offentlige Utredninger, "Et Norge uten Miljøgifter," Nov. 2010.

[17] M. M. Williams and M. Mergel, "Electronic Waste (E-Waste) - Toxipedia," Mar. 2011.

[18] K. Roebuck, *RoHS/WEEE: High-impact Strategies - What You Need to Know: Definitions, Adoptions, Impact, Benefits, Maturity, Vendors*. Emereo Publishing, Oct. 2012.

[19] CM consulting, "Elements and Substances of Concern in WEEE," 2013.

[20] Greenpeace, "Toxic Tech - Chemicals in Electronics," May 2005.

[21] S. M. Ogilvie, "WEEE & Hazardous Waste -A report produced for DEFRA," Mar. 2004.

[22] A. Buekens and J. Yang, "Recycling of WEEE plastics: a review," *Journal of Material Cycles and Waste Management*, vol. 16, pp. 415–434, Mar. 2014.

[23] E. Dimitrakakis, A. Janz, B. Bilitewski, and E. Gidarakos, "Small WEEE: Determining recyclables and hazardous substances in plastics," *Journal of Hazardous Materials*, vol. 161, pp. 913–919, Jan. 2009.

[24] S. G. Gilbert, *A Small Dose of Toxicology: The Health Effects of Common Chemicals, Second Edition*. CRC Press, 2 edition ed., July 2009.

[25] Miljødirektoratet, "Miljøstatus i Norge : Arsen," Oct. 2014.

[26] E. Grzincic and S. Gilbert, "Cadmium (Cd) - Toxipedia," July 2014.

[27] Miljødirektoratet, "Miljøstatus i Norge : Kadmium," Jan. 2014.

[28] I. A. Darwish and D. A. Blake, "Development and Validation of a One-Step Immunoassay for Determination of Cadmium in Human Serum," *Analytical Chemistry*, vol. 74, pp. 52–58, Jan. 2002.

[29] D. Sutoo, K. Akiyama, and S. Imamiya, "A mechanism of cadmium poisoning: The cross effect of calcium and cadmium in the calmodulin-dependent system," *Archives of Toxicology*, vol. 64, pp. 161–164, Mar. 1990.

[30] Miljødirektoratet, "Miljøstatus i Norge : Krom," Feb. 2014.

[31] S. G. Gilbert, "Lead - Toxipedia," Mar. 2014.

[32] Miljødirektoratet, "Miljøstatus i Norge : Bly," Feb. 2014.

[33] K. Lah, "Biological Properties of Lead - Toxipedia," Aug. 2011.

[34] S. G. Gilbert and B. Weiss, "A rationale for lowering the blood lead action level from 10 to 2 ug/dL," *NeuroToxicology*, vol. 27, pp. 693–701, Sept. 2006.

[35] M. Mergel, "Health Effects of Lead - Toxipedia," Oct. 2010.

[36] Lovdata, "Forskrift om tiltaksverdier og grenseverdier for fysiske og kjemiske faktorer i arbeidsmiljøet samt smitterisikogrupper for biologiske faktorer (forskrift om tiltaks- og grenseverdier) - Lovdata," 2011.

[37] S. Gilbert and M. Gaither, "Mercury - Toxipedia," Sept. 2014.

[38] Miljødirektoratet, "Miljøstatus i Norge : Kvikksølv," June 2014.

[39] K. Lah and M. Mergel, "Dioxin - Toxipedia," Mar. 2011.

[40] Miljødirektoratet, "Miljøstatus i Norge : Dioksiner og furaner," June 2014.

[41] EPA, "EPA's Reanalysis of Key Issues Related to Dioxin Toxicity and Response to NAS Comments, Volume 1," 2012.

[42] Miljødirektoratet, "Miljøstatus i Norge : PCB," Mar. 2014.

[43] Miljødirektoratet, "Miljøstatus i Norge : Hormonforstyrrende stoffer," Apr. 2014.

[44] Miljødirektoratet, "Miljøstatus i Norge : Bromerte flammehemmere," Mar. 2014.

[45] Miljødirektoratet, "Miljøstatus i Norge : Fosfororganiske flammehemmere," Mar. 2014.

[46] Miljødirektoratet, "Miljøstatus i Norge : Bisfenol A," Mar. 2014.

[47] Miljødirektoratet, "Miljøstatus i Norge : Ftalater," June 2014.

[48] S. Gilbert, "PVC - Toxipedia," Jan. 2011.

[49] A. Julander, L. Lundgren, L. Skare, M. Grandér, B. Palm, M. Vahter, and C. Lidén, "Formal recycling of e-waste leads to increased exposure to toxic metals: An occupational exposure study from Sweden," *Environment International*, vol. 73, pp. 243–251, Dec. 2014.

[50] M. Aucott, M. McLinden, and M. Winka, "Release of Mercury from Broken Fluorescent Bulbs," *Journal of the Air & Waste Management Association*, vol. 53, pp. 143–151, Feb. 2003.

[51] F. Zimmermann, M.-T. Lecler, F. Clerc, A. Chollot, E. Silvente, and J. Grosjean, "Occupational exposure in the fluorescent lamp recycling sector in France," *Waste Management*, vol. 34, pp. 1257–1263, July 2014.

[52] E. H. Page and D. Sylivan, "Exposure to Hazardous Metals During Electronics Recycling at Four UNICOR Facilities," Dec. 2009.

[53] D. M. Ceballos, W. Gong, and E. Page, "A Pilot Assessment of Occupational Health Hazards in the U.S. Electronic Scrap Recycling Industry," *Journal of Occupational and Environmental Hygiene*, p. 0, Mar. 2015.

[54] D. Ceballos, L. Chen, E. Page, A. Echt, A. Oza, and J. Ramsey, "Evaluation of Occupational Exposures at an Electronic Scrap Recycling Facility," July 2014.

[55] L. S. Morf, J. Tremp, R. Gloor, Y. Huber, M. Stengele, and M. Zennegg, "Brominated Flame Retardants in Waste Electrical and Electronic Equipment: Substance Flows in a Recycling Plant," *Environmental Science & Technology*, vol. 39, pp. 8691–8699, Nov. 2005.

[56] C. Rosenberg, M. Hämeilä, J. Tornaeus, K. Säkkinen, K. Puttonen, A. Korpi, M. Kiilunen, M. Linnainmaa, and A. Hesso, "Exposure to Flame Retardants in Electronics Recycling Sites," *Annals of Occupational Hygiene*, vol. 55, pp. 658–665, July 2011.

[57] A. Sjödin, L. Hagmar, E. Klasson-Wehler, K. Kronholm-Diab, E. Jakobsson, and A. Bergman, "Flame retardant exposure: polybrominated diphenyl ethers in blood from Swedish workers.," *Environmental Health Perspectives*, vol. 107, pp. 643–648, Aug. 1999.

[58] A. Sjödin, H. Carlsson, K. Thuresson, S. Sjölin, k. Bergman, and C. Östman, "Flame Retardants in Indoor Air at an Electronics Recycling Plant and at Other Work Environments," *Environmental Science & Technology*, vol. 35, pp. 448–454, Feb. 2001.

[59] K. Thuresson, k. Bergman, K. Rothenbacher, T. Herrmann, S. Sjölin, L. Hagmar, O. Päpke, and K. Jakobsson, "Polybrominated diphenyl ether exposure to electronics recycling workers – a follow up study," *Chemosphere*, vol. 64, pp. 1855–1861, Sept. 2006.

[60] A. Searl and J. Crawford, "Review of Health Risks for workers in the Waste and Recycling Industry," May 2012.

[61] CM consulting, "The WEEE Report - Waste electrical and electronic Equipment Reuse and Recycling in Canada - 2013," 2013.

[62] B. A. Fowler, M. Schubauer-Berigan, and C. J. Hines, "Indium phosphide and other indium compounds," 2006.

[63] Miljødirektoratet, "Miljøstatus i Norge : Miljøstatus 2009," 2009.

[64] EE-registeret, "EE-registeret," 2015.

[65] Lovdata, “Forskrift om gjenvinning og behandling av avfall (avfalls-forskriften) - Kapittel 3. Kasserte batterier - Lovdata,” Oct. 2012.

[66] Miljødirektoratet, “Når EE-produkter blir avfall,” 2015.

[67] E. Husby, “Norsk Gjenvinning,” July 2015.

[68] P. H. Øveren and R. A. Olsen, “Renas,” July 2015.

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no