Present and potential future recycling of critical metals in WEEE

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Context

The paper was originally prepared for the European Environment Agency (EEA) under its 2011 and 2012 work programmes as a contribution to the EEA's work on policy analysis and assessment.

Disclaimer

This paper was delivered to the EEA in 2012. In February 2014 the EEA decided not to publish it. The EEA recognised the considerable and valuable contributions, but felt the available data was not strong enough to support reliable and robust estimations and conclusions.

CRI, with the cooperation of the report authors, felt that the work, while challenging, was a useful contribution to the development of WEEE management and should be made publicly available for a broader audience. No other quantitative assessments have so far been published regarding the extent to which recycling of critical metals from WEEE can contribute to the European need. All assumptions and estimations are transparent and fully described within the report. The responsibility for the contents of the report remains with the authors.

Note on the data used in this report.

The analysis for this report was completed in April 2012. The data used within, while current at the time of writing, may have since been updated.

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Acknowledgements

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The project manager was Christian Fischer. Industrial stakeholders provided valuable input to the report on two separate occasions:

- First, during a stakeholder workshop on Recycling of Critical Metals in WEEE arranged by the European Environment Agency (EEA) on 14th September 2011. The following participants gave valuable inputs: Christian Hagelüken, Umicore; Johan Holmqvist, Sony-Ericsson; Horst Bröhl-Kerner, Recyclingzentrum Frankfurt; Kai Kramer, Electrocycling Goslar; Peter J. Niss, Saubermacher Dienstleistungs AG; Markku Ojalehto, Boliden; Sverker Sjölin, Stena Technoworld; Bill Skeates, Samsung and DIGITAL EUROPE; Bodil Anette Stenholt, Sony; and Alain Vassart, EBRA – European Battery Recycling Association.

- Second, during the review of the draft paper, submitted to the workshop participants. Some very important comments were provided by: Sylvie Feindt, DIGITAL EUROPE; Christian Hagelüken, Umicore; Sverker Sjölin, Stena Technoworld; Bill Skeates, Samsung and DIGITAL EUROPE; and Bodil Anette Stenholt, Sony. Thanks are due to all contributors who generously offered data, comments, and an overall valuable contribution to this report.

Summary

This report details current and potential recycling of critical metals in Waste from Electrical Electronic Equipment (WEEE). The term 'critical metals' is used instead of 'rare metals' because the concept incorporates not only supply but also demand. The EU needs access to these metals and recycling can be an important part of the supply-strategy.

The included metals and products
The selection of the critical metals is based on *three supply risk elements*:

1) Reserve –to-production ratio;
2) Regional concentration of reserves and;
3) Lack of suitable recycling technologies,

…and *three demand or economic elements*:

1) Rapid growth in demand;
2) Price development and,
3) Relevance of Electrical and Electronic Equipment (EEE) in metal consumption.

An assessment of 60 metals based on these criteria identified thirteen metals, which have been sub-divided into two groups based on importance:

Group 1	Silver, Cobalt, Indium, Lithium, Tantalum, Tellurium and Tungsten
Group 2	Gold, Beryllium, Gallium, Germanium, Palladium and Ruthenium

These metals are found mainly in the following Electrical and Electronic Equipment-components (EEE-components) and EEE-product groups:

1) Mobile phones;
2) Personal Computers (desktop computers),
3) Laptops and notebooks;
4) TV and flat screen monitors and,
5) Rechargeable batteries (as contained in WEEE).

We have also included thin film and conventional crystalline solar power converters (photovoltaic cells) because they also contain these critical metals, although the quantity of waste from photovoltaic cells is currently low.

Assessment of the potential amount of future WEEE
About 3.1 million tonnes of WEEE was reported collected in the EU in 2008, but it is estimated that around 7 to 8 million tonnes of WEEE was generated, equal to a collection rate about 40 %. This report addresses that part of the collected WEEE belonging to the above identified EEE- product groups and solar power converters.[1]

[1] There are several reasons why the reported figures may not reflect the full extent of WEEE collection and processing. First of all it includes mainly WEEE from households, and as such misses an unknown quantity of non –household WEEE. The recent recast of the WEEE Directive (EU-Commission, 2012) will lead to higher collection and recycling targets, the removal of the distinction between household and non-household WEEE and further measures to combat illegal exports. These changes are expected to lead to more WEEE being collected, processed and recorded through the official WEEE systems.

EU-sales have been estimated for the period 2000 to 2015, based on Eurostat data on the sales of the selected product groups in the years 2007, 2008, 2009, and some country specific data in the period from 2005 to 2010. In order to calculate when these sold products will become waste; a lifetime distribution for the selected product groups has been undertaken. Based on this, the generation of waste of the selected product groups has been calculated to be about 254 000 tonnes in 2008, 340-000 tonnes in 2010 and 640 000 tonnes in 2015. Due to the long life-time of solar energy panels, only a very limited amount of this waste will be generated by 2010 and 2015. The potential recycling of critical metals in solar power converters has therefore not been included in the further work, but photovoltaic waste is expected to be a potential recovery source for critical metals (such as indium) in the future.

Assessment of the potential amount of critical metals in the selected product groups
It was originally intended to use information about critical metals on the level of product groups and the individual components. However, it has been more difficult than expected to get precise information about the critical metal content in the selected product groups, let alone the content of critical metal in the individual components. Often the product- or component-producers themselves do not have sufficient information about content and location of specific critical metals. In some cases, this is because the producers are reluctant to provide such information, but very often to the highly complex supply chains for EEE products and components makes it very difficult for producers to trace exact compositions of products and components. The original equipment producer focuses on functionality and legal requirements like the EU Directives on chemicals (REACH) and hazardous substances in EEE (ROHS).

This problem has been overcome by using product material composition data from a study undertaken by the Japanese Ministry of the Environment and Ministry of Economy, focussing specifically only on the product group level. This has allowed the calculation of an estimate for total amount of critical metals contained in waste from the selected product groups in 2008, 2010 and 2015.

In total, about 2 000 tonnes of critical metals could potentially be recovered in 2008, 2 300 tonnes in 2010, and 3 000 tonnes in 2015. Around of 83 % of these quantities by weight is cobalt, primarily from mobile phone and laptop batteries.

Assessment of the actual and potential amount of recycled critical metals
One thing is the actual content of critical metals in the selected product groups; another thing is whether they can be recycled. The recovery rate is, in the first instance, dependent on the collection of discarded products as WEEE, and also that these discarded products (WEEE) are not exported out of the EU disguised as old or second hand products. The efficiency of the pre-processing and end-processing processes and to what extent the technical-organisational interface between these subsequent steps is appropriately managed is also critical in determining the overall recovery rate for the metals.

The pre-processing efficiencies of the critical selected metals from complex products are very much dependent whether the dismantling is manually, combined manually-mechanically or fully mechanically undertaken. For example, the recovery rate of gold, silver, palladium and indium in PCs or laptops can be as high as 90 % for part-manual pre-processing (removal circuit boards with subsequent mechanical processing of remaining parts), but only 24 % when full mechanical recovery is used (Chancerel, 2010). The end-processing efficiency rates of metals vary a great deal. This is largely dependent on the metals involved rather than the origin of the scrap. It also depends heavily on which kind of end-processing route is selected. While state-of-the-art integrated smelter-refineries can recover a wide range of metals with high yields (E.g. precious metals > 95 % with co-recovery of a number of special metals and even of some indium) less sophisticated end-processing can lead to

significant losses. Innovative dedicated recovery processes for batteries can achieve > 90 % yield of cobalt and also recover lithium. However certain metals - such as tantalum or tungsten – will get lost even in most advanced processes, if occurring in mixes with, for example, copper or precious metals.

In other words, the recycling of critical metals is very much dependent on the weakest point in the recycling chain. Low collection rates and an inappropriate sequence of recycling steps seriously retard recycling rates. The total recycling efficiencies for the thirteen critical metals along the entire recycling chain for the product groups assessed has been calculated to be:

- Mobile phones: from 0 – 5 %
- Desktop computers: from 0 – 40 %
- Laptop PCs: from 0 – 15 %
- TV and flat screen monitors: from 0 – 15 %
- Rechargeable batteries in mobile phones and laptops: from 0 – 15 %

If all the critical metals in products within the selected product groups were recycled when the products become waste, it would of course help fulfil the demand for critical metals.

For example, waste laptop PCs, mobile phones, desktop PCs and flat screens contained about 3.4 tonnes of indium in 2008, about 4.6 tonnes in 2010 and will contain a projected 9.2 tonnes in 2015. The global demand for indium within these products was around 57.6 tonnes in 2009[2] and the global demand of indium for total EEE was 420 tonnes in 2010. This means that full EU recovery of the indium from the four product categories above could fulfil approximately 7 % of the global demand for indium for the same product categories. For most of the other metals the coverage rate is lower than 10 %.

The above percentage is lower than initially anticipated, which could be the result of a number of factors. First of all, it has been necessary to include many assumptions in the calculations: information on the sales volume of the selected products is limited, we do not know exactly how much of each of the critical metals are contained in the selected products, or the composition of the current collection of WEEE, and the model assumes a production efficiency of 100 %, which we know not to be a true reflection of the industrial processes used.

In addition, some industrial EEE that is not sold in large volumes but contain a larger amount of critical metals could have been missed.

[2] This is based on the quantity of indium calculated to be *contained* within the products sold globally in 2009. As such, the “demand” for the metal assumes a production efficiency of 100%.

Economic importance
The critical metals in WEEE that are not recycled also represent an economic loss. For the selected product groups this loss been calculated to be in the region of 1.65 billion Euros in 2010. In addition, improved and increased recycling of WEEE can be expected to generate new jobs. It is estimated that the increase of collection of WEEE according to the new EU WEEE Directive totally would generate at least 12 000 new jobs.

Conclusions
The study shows that the current recycling of critical metals in WEEE is very low, but that the potential amount could be increased threefold within 2015. Improving of the recycling of critical metals requires a variety of initiatives tackling different week point in the overall process: better collection, better pre-processing and end-processing, limiting the export of WEEE or used products out of the EU and better design of the EEE-products.

This study shows that data on sales volumes, WEEE composition and the composition of critical metals in EEE is currently insufficient for detailed analysis and monitoring, and addressing this should be a priority. Further, more detailed information on components used in EEE product groups would enable recyclers to identify and access the most materially important components. Dialog between recyclers, smelters and manufacturers could also facilitate product design that supports the recycling process.

1 Context and objectives

This working paper aims to illustrate how the recycling of WEEE[3] can potentially contribute to the increased material and resource efficiency of *critical* metals.

The term "resource efficiency" can refer to different levels of activity; for example the overall economy, or individual industrial sectors.

The importance of critical metals for the manufacture of Electrical and Electronic Equipment (EEE), and concentration of these materials in EEE makes the proper management of WEEE critical for the increased resource efficiency of these materials. To improve the material and resource efficiency of critical metals, specific actions are required to enhance the quality and/or efficiency of recycling by – among others – avoiding losses and down-cycling of critical metals.

To analyse the scope for increasing the recovery of critical metals from WEEE, it is necessary to examine the types and quantities of critical metals in WEEE, the efficiency of the WEEE collection system, the nature of the recycling processes and the outputs from these processes.

The EU still lacks a comprehensive recycling system for WEEE, and the proportion of WEEE separately collected for processing is currently low, while the handling methodologies and recycling technologies themselves also give rise to losses of critical metals.

1.1 Quantitative and qualitative targets

In 2005, the European Commission formulated a vision for the EU as a recycling society within its thematic strategy for waste prevention and recycling[4]. In order to increase recycling, the EU has introduced a variety of recycling policies over the past 15 years, including specific recycling targets for different end-of-life products including waste electrical and electronic equipment, end of life vehicles, packaging, and batteries. A common theme across these initiatives is that they focus on reaching minimum *quantitative* recycling targets by a given year. These targets mean that a minimum percentage of the particular waste stream has to be recycled. Recycling can enhance resource efficiency by reducing the use of virgin materials, while also reducing the environmental impacts related to the extraction and processing of virgin materials.

[3] WEEE (Waste Electrical and Electronic Equipment) in this report is used for items covered by the different waste categories in the WEEE Directive including the batteries in the discarded products plus also solar panels although at the moment this product group is not covered by the WEEE Directive 2002/96/EC (EU-Commission, 2002). According to this Directive 'recycling' means: "The reprocessing in a production process of the waste materials for the original purpose or for other purposes, but excluding energy recovery which means the use of combustible waste as a means of generating energy through direct incineration with or without other waste but with recovery of the heat". The Commission has on 24th July 2012 published the recast of the WEEE Directive (EU-Commission, 2012). The definition of 'recycling' in the new Directive follows now the definition included in the Waste Framework Directive (2008/98/EC), which however does not make any substantial difference compared to the old definition. The new WEEE Directive has to be transposed by the Member States by latest 14th February 2014.

[4] EU-Commission, 2005: Communication from the Commission on the Thematic Strategy on the Prevention and Recycling of Waste

The general quantitative recycling targets for the different end of life products imply that materials within that waste stream are treated equally; the Directives' targets regard the recycling of one ton of iron the same as recycling one ton of gold, although it is much easier to recycle one tonne of iron.

However, in recent years the EU has placed greater focus on the fact that certain materials are more essential than others for the EU economy. In 2010, an ad-hoc group under the European Commission in close co-operation with Member States and stakeholders identified 14 raw materials, mainly metals, which are of high importance for the EU economy and show a high supply risk[5]. The limited availability of these metals could negatively affect the possibilities of producing and using new technologies that can maintain a sustainable energy supply and achieve information technology advancements.

Increasing recycling of these more critical materials (especially metals), can be an important part of a strategy that would secure continued access to these metals. This will require a greater focus on the *qualitative* aspects of the recycling of metals, as many of these critical metals are characterised by a dissipative use; that is to say they are used in small amounts throughout a multitude of application areas or products. The existing recycling policy and infrastructure - the current forms of collection and recycling techniques - have not yet focused on this problem, meaning that many of these critical metals are not recovered.

In 2010 and 2011, other studies focused on critical metals and in which products or application areas they can be found, for example, in projects undertaken by the German EPA and the English EPA[6].The work undertaken by the ETC/SCP in this paper focuses on critical metals in the waste electrical and electronic products (WEEE). Not all of the product groups of WEEE are included in this assessment as the study focuses on those considered the most relevant with regard to critical metals.

Better recycling of WEEE will not only improve access to critical metals in the EU, it will also have positive socio-economic impacts such increasing jobs and economic turnover. In this way, recycling of WEEE and the associated recovery of critical metals can contribute to a greener economy; this potential is also covered in this report.

1.2 Objectives

The objectives of this report are to provide:

1. An assessment of the amount of critical metals in 2015 which potentially could be recycled from selected WEEE product groups;
2. An analysis of critical metal losses in existing collection, dismantling, pre-processing and end-processing processes for selected WEEE product groups;
3. An estimate of the socio-economic benefits of better WEEE recycling; and
4. Proposals to improve the efficiency of the (entire) recycling process chains.

[5] EU-Commission, 2010: Critical raw materials for the EU

[6] UBA, Germany, 2011 and Environment Agency-England & Wales, 2011

1.3 Procedural approach

The methodology for this study involved the following steps:

Step I – Chapter 2 & 3

a) Selection of critical metals.
b) Selection of products containing those metals.

Step II – Chapters 4 & 5

a) Calculating actual and potential collection of the selected WEEE products.
b) Calculating the WEEE generated in 2015 from these products. (achieved by combining sales data and expected lifetime data)
c) Estimating the total efficiency of pre- and end- processing of the selected metals in the selected products.

Step III – Chapter 6

a) Calculate the actual and potential recycling of the selected critical metals from the selected products.
b) Relate these amounts to the EU demand for these critical metals and the economic value of the metals.

The approach has been developed and continuously refined during the conduct of the project. Despite certain data bottlenecks, a maximum of methodological consistency across product group has been preserved.

The project has been conducted in close dialogue with many stakeholders within the EEE and the WEEE sectors. Although the stakeholders have provided useful information and participated in a workshop, it has been more difficult than anticipated to obtain the necessary data for making the required calculations. Therefore, it has been necessary to make many assumptions in order to undertake the calculations. For the sake of transparency, these assumptions are all stated in the report, which sometimes makes the reading a little bit heavy.

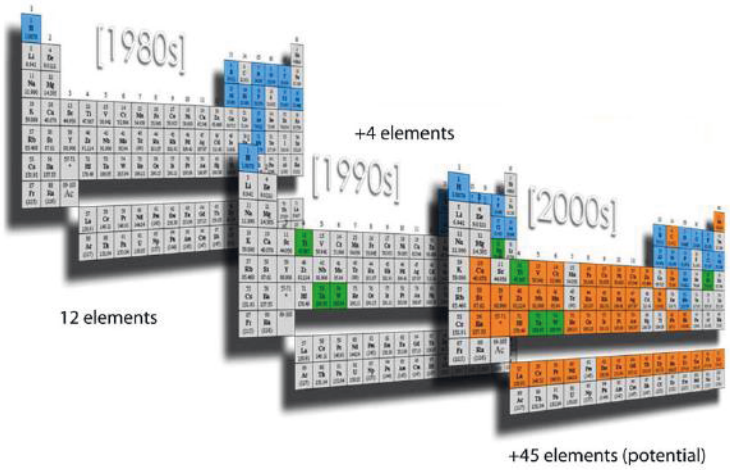
2 Critical metals in Electrical and Electronic Equipment

2.1 The use of critical metals in electrical and electronic equipment

"The electronics sector that includes computing, communication, entertainment, and dozens of other applications is demonstrative of the dynamic nature of changing mineral and mineral suite applications that have facilitated technological advances. Miniaturisation, energy efficiency, and increased processing or operating speed, are some of the product performance goals that have driven research to optimise the properties of minerals or mineral products to meet new performance specifications" (NRC, 2008).

As a consequence of continuous modifications of function and design of appliances, electrical and electronic equipment (EEE) contains a highly heterogeneous mix of materials. Essential constituents of much EEE include so-called *critical metals*[7] comprising precious metals (gold, silver, and palladium) and special metals (indium, selenium, tellurium, tantalum, bismuth, antimony) (cf. Chancerel, 2010). Figure 1 illustrates this development taking the example of computer chip technology: In the 1980s, computer chips were made with a palette of twelve elements; a decade later, 16 elements were employed. Today, as many as 60 different elements are used in fabricating integrated circuits (cf. NRC, 2008). A large number of these elements are used as compounds or alloys formed with other elements. These chemical compounds or alloys possess unique electrical, dielectric, or optical properties based on their atomic structure.

Figure 1: Rapid developments in the application of elements by computer chip technologies



Source: NRC (2008)

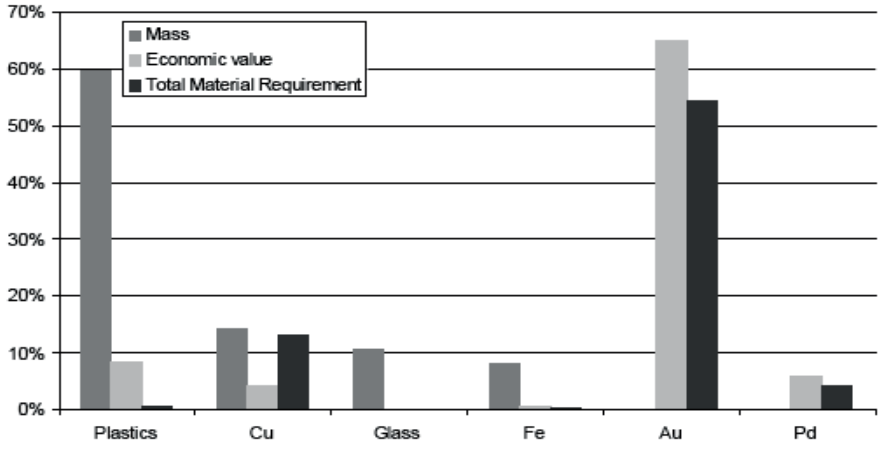
[7] The term *critical metals* as used in this paper comprises a group of metals, which show demanding supply risks and economical relevance despite low metal volumes and low perception in the past. The term is introduced more profoundly in chapter 3.

2.2 Ecological Relevance of Critical Metals in EEE

The manufacture of components and the use of electrical and electronic devices are often responsible for the bulk of the life-cycle-wide environmental impacts of EEE (Koomey, 2008; Koomey et al., 2009; OECD, 2010). The ecological relevance of the different components differs between the diverse EEE, as does their mass distribution. On the basis of weight, steel and plastics are the two dominant materials used in EEE. Obviously, the weight distribution of the different substances differs from the value distribution and so does the distribution of related environmental pressures.

For example, gold in mobile phones accounts for less than 1 % of the device weight, but at the same time accounts for over 50 % of the material flows induced by its production (resources extraction used and unused, in terms of *total material requirement*[8]) (Figure 2). This indicates that relative shares of the environmental pressures could be correlated to a certain degree with the use critical metals.

Figure 2: Distributions of mass, of economic value and of Total Material Requirement among the constituting metals and materials in mobile phones



Source: Chancerel et al. (2009

Clean room environments as required for the manufacturing of electronic components demand significant amounts of energy for ventilation and air filtration (Xu, 2001). During the manufacturing process, in particular of active components containing silicon circuitry, most of the environmental pressures are related to energy use, large consumption of deionised water, the preparation of high-purity silicon and dopants, and the production of chemicals including bulk gases, acids, developers, etc. (Krishnan et al., 2008; Pleplys, 2004 and Williams, 2008). For instance, the manufacturing of a 2 gram 32 MB DRAM chip requires 1 600 g of fossil fuels and 72 g of high purity chemicals (Williams et al., 2002).

While the energy and material efficiencies of the semiconductor industry have been improving on a per unit basis, the semiconductor components become more complex, requiring additional manufacturing steps and purer and more "exotic" ingredients (cf. Figure 1). It is – among others – the combination of both high levels of purity of the ingredients and

[8] The *total material requirement* (TMR) is an indicator comprising both the used extraction and the unused extraction associated with the material extraction, the so-called "hidden" material flows (i.e. the material rucksack).

low concentrations in the corresponding ores that cause significant environmental burdens stressing the potential of mitigation by the recycling of critical metals in WEEE.

Depending on the design of waste management systems and handling technologies for WEEE, significant environmental impacts can also take place at the end of life of EEE (Eugster et al., 2007; Hischier et al., 2005).

2.3 Economical Relevance of Critical Metals in EEE

In 2009, the European Union (EU) exported €86bn and imported €157bn worth of electronics (electronic components, computer and office equipment, telecommunication equipment and consumer electronics) excluding electric appliances.[9] With regard to the value of materials, precious metals account for a significant part of the value of computers, cell phones, calculators, television boards, and digital versatile disc (DVD) players (Chancerel, 2010).

The overall European Electrical Engineering Industry (EEI) that manufactures products ranging from consumer goods to turbines, trains, power grids and power stations, has employed ca. 2.8 million people (2007) with an overall production of €411bn (2008). The share of EEI products in EU exports was about 10 % resulting in a slightly positive trade balance for EEI products in 2008. With 21 % of the global production of EEI products, the EU occupied second spot after China (30 %), ahead of the USA and Japan (both 19 %).[10]

The semiconductor sector in the EU employs 215 000 workers (105 000 in equipment and materials, 110 000 in device making) and generates around 10 % of the European GDP. Equipment and materials suppliers contribute with €9bn and semiconductor device makers with €20bn to the EU economy. The semiconductor sector's value chain thus plays a significant role with regard to the national GDP of Austria, Belgium, France, Germany, Ireland, Italy, Malta, the Netherlands, and the UK. For Germany, actually 80 % of its exports depend in some way on ICT, and semiconductors enable the generation of 10 % of its GDP.[11]

Furthermore, WEEE has become one of the fastest growing fractions of municipal solid waste (cf. UNU, 2008, 3). Considering the multitude of actors and products, the rapid changes of technology, product design and related material composition, as well as the rather opaque life cycle chains, WEEE is one of the most complex waste fractions. In addition, the security of supply of metals has become increasingly important for business and complete industry sectors, as stated by the European Commission:

"Metals are […] essential to modern industrial activity as well as to the infrastructure and products used in daily-life. […] Modern cars, flat-screen televisions, mobile phones and countless other products rely on a range of materials, such as antimony, cobalt, lithium, tantalum, tungsten and molybdenum. The same group of high-tech metals are also fundamental to new environmentally friendly products, with electric cars requiring lithium and

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9 European Commission. Trade.
URL: http://ec.europa.eu/trade/creating-opportunities/economic-sectors/industrial-goods/electronics

10 European Commission. Enterprise and Industry.
URL: http://ec.europa.eu/enterprise/sectors/electrical/competitiveness

11 European Metalworkers' position paper.
URL: http://ec.europa.eu/enterprise/sectors/ict/files/peter_scherrer_emf_position_on_semiconductors_en.pdf

neodymium, car catalysts requiring platinum, solar panels (partly) requiring indium, gallium, selenium and tellurium, energy efficient high-speed trains requiring cobalt and samarium, and new fuel-efficient aircraft requiring rhenium alloys" (EC, 2010a, 11).

2.4 Structural Scarcity

Critical metals are often not mined as main products, but rather occur as by-products of mining operations primarily developed for the extraction of other metals. However, prices for by-products tend to be inelastic: rising prices do not necessarily result in increasing production. This is because mining investments are strongly correlated with the expected monetary return from the production of the main products, not one of the by-products.
The same is principally true for the production of metals from secondary resources, as recycling activities are basically driven by the main products of the recycling processes[12]. Due to the missing incentives for mining investments for by-products, the supply-demand-relationship is partly not balanced. Critical metals, which are neither a main product in primary production nor in secondary production, are therefore predestined for the risk of insufficient supply. Such scarcity is called structural scarcity or technical scarcity as the reasons are not caused by limited ore deposits, but rather by economic or technical boundary conditions for the mining and production of the critical metals.

[12] It should be noted that the critical metals can be a main product in the primary production, while being a by-product in the secondary production, or vice versa.

3 Methodology

3.1 Description of previous relevant studies

Several research projects have investigated metals used by different technologies with regard to the dimensions 'criticality', ‘rarity’ or ‘scarcity’, including the consideration of potential supply risks. However, these studies differ in scope and coverage. They also use a ‘common applied criteria’ (so-called filter criteria) according to their topic and coverage, and/or to focus on a selection of metals or materials. This study covers the three above-mentioned dimensions applied to metals, resulting in the terms ‘critical metals’, ‘rare metals’ and ‘scarce metals’. It is the aim of this chapter to exemplify the diversity of existing methodological approaches rather than to create a comprehensive list of such studies.

Comparing the different studies and reports, it becomes obvious that there is no uniform definition of ‘critical metals’. In general, objects are labelled as ‘rare’ in order to indicate a low frequency in proportion to other objects. But this frequency can refer to very different properties or qualities – leading to very different interpretations. Following the definition of several studies, a material can be regarded as critical only if it performs an essential function for which few or no satisfactory substitutes exist. This dimension of criticality is therefore related to the demand for a metal that meets very precise specifications required in certain key applications, but is not simply related to overall demand for all applications (cf. NRC, 2008).

The term ‘critical metals’ has to be distinguished from the term ‘strategic metals’. The term ‘strategic metal/mineral’ is almost entirely exclusively linked with national security and military needs, or requirements during national emergencies. In contrast, a ‘critical material’ has broader and more deeper connotations as its definition can be considered to include civilian, industrial, and military applications, which could have measured effects on the domestic economy and welfare, in the event of the supply of a metal under evaluation would become restricted. The technical literature (also beyond the studies mentioned above) provides diverse definitions for the terms ‘critical metals’, ’rare metals’ and ‘scarce metals’, subject to the context of the articles. For example, scarcity has been defined as a “state in which actual or expected demand of resources exceeds its availability. Resource scarcity can occur locally, regionally or globally [...]” (UBA, in preparation).

Depending on the purpose of the study several types of mineral scarcity can be distinguished. Two examples are given in the following:

- The Resource Glossary of the Federal Environment Agency (DE) distinguishes with respect to its causes and effects on resource markets:
    - Physical scarcity;
    - Political scarcity;
    - Speculative scarcity;
    - Temporary scarcity (time lag between demand and installation of production capacities);
    - Economic (price) scarcity.
- Shields and Solar (2010) distinguish:
    - Mineral scarcity;
    - Physical scarcity (fixed stock paradigm, opportunity cost paradigm);
    - Situational scarcity;
    - Political scarcity;
    - Social scarcity.

3.2 Methodological Conclusions for the Selection of Metals

Although the three dimensions 'criticality', 'rarity' and 'scarcity' overlap to a certain degree, the objectives of this study point to the use of 'critical metals'. The preference for this term can be explained as follows:

- 'Critical metals' is preferred to 'rare metals' as it comprises both the supply of and the demand for the metals (rather than 'rare metals' that commonly disregards the demand for the metals);
- 'Critical metals' is preferred to 'scarce metals' as it already anticipates expectations of future risks, and can generally be extended by further non-economic dimensions, e.g. environmental relevance (not implemented so far).

Based on the objective of the study, the following criteria were applied for the selection of metals. The criteria can be grouped into two dimensions: *supply risk* and *economic relevance*. This is line with the definition developed by the EU Raw Material Initiative which labels a raw material as "critical when the risks of supply shortage and their impacts on the economy are higher than for most of the other raw materials" (EU-Commission, 2010). Nevertheless, slightly different indicators for the two dimensions have been developed with the chosen focus on electronic equipment.

3.2.1 Supply risks

Reserve-to-production ratio

The reserve-to-production ratio represents the time interval, for which the production of a certain metal can be maintained assuming:

- A constant production volume amounting to today's volume (constant demand), and,
- Fixed reserves (figures of reference year), independent from technology and market development.

A reserve-to-production ratio below 50 years is considered to reflect the need or urgency for exploration of either primary or secondary[13] resources.

This measure cannot be interpreted as a prediction of the lifetime of the overall share of exploitable resources, as both the production and the demand volumes are variable over time and influenced by various interdependent factors. This is especially true for some critical metals that have 'premature markets' that feature relatively low supply/demand figures.

Regional concentration of reserves

Another relevant issue besides economic scarcity of mining ores is the political availability of resources, especially in times of increased commodity prices where elements of protectionism and resource nationalism gain importance. A significant share of relevant resource deposits is located in countries with rather unstable or unpredictable political conditions and structures. In that way, a concentration of more than 90 % of the reserves within the major three mining countries of that metal are considered as political risk for its availability (medium- to long-term risk).

[13] The term "secondary reserves" refers to the recycling market.

Lack of suitable recycling technologies
Secondary resources include metals discarded in landfills, metals still in use, for example in long-lasting infrastructure systems, or metals in hibernating stocks. Although the relevance of these resources is increasing, so far only minor fractions of metals undergo high-quality recycling due to adverse economic conditions, insufficient infrastructure or technical limitations. Especially for the short to medium term, the quantity of material available for recycling may often meet only a modest proportion of future demand. For the purpose of this study, the non-existence of an established economic technology for the recycling of end of life consumer products is considered as a criterion.

3.2.2 Economic relevance

Rapid growth in demand
High rates of demand growth can be interpreted as an indicator for the (expected) economic relevance of a certain metal: as a general trend, the products in which or for whose production the metals are used, meet an increasing demand. Furthermore, an expected future rapid demand growth also increases temporal supply risks with regard to these metals, as the planning and developing of new mines can take some 5-15 years.

Table 1 represents a selection of emerging EEE technologies by the Ad-hoc Working Group of the European Commission, indicating metals with the above-mentioned characteristics (cf. EU-Commission, 2010). The increase in their demand is estimated to exceed 50 % to 2020.

Table 1: Main applications of selected metals

Metal	Applications
Silver	Radio Frequency Identification tags (RFID), lead-free soft solder
Cobalt	Lithium-ion batteries, synthetic fuels
Copper	Efficient electric motors, RFID
Gallium	Thin layer photovoltaics, Integrated Circuit (IC), white light-emitting diodes (WLED)
Germanium	Fibre optic cable, IR optical technologies
Indium	Displays, thin layer photovoltaics
Niobium	Micro capacitors, ferroalloys
Neodymium	Permanent magnets, laser technology
Antimony	Antimony-tin oxide (ATO) used in display panels, micro capacitors; flame retardants used in EEE plastics
Tantalum	Micro capacitors, medical technology

The Ad-hoc working group has identified the listed metals as critical, if a demand increase of 50 % or more can be expected based on expert judgment in different studies (cf. EU-Commission, 2010, NRC 2008, RWI/ISI/BGR 2006). This criterion is also applied for this study.

Price development
Rising prices can be expected if the increasing demand of a metal cannot be compensated by an increased supply. This is especially the case if certain metals are produced only as by-products of base metals (e.g. indium or germanium from zinc mines or gallium from aluminium processing) and show a very low price elasticity of supply. Steep price developments also indicate the lack of appropriate substitutes for the metal. Moreover, prices can rise due to speculation reflecting expectations for demand increases in the future. Rising prices on the one hand increase the economic relevance of an industry sector; on the other hand they create new incentives for optimised recovery of these metals.

For the purpose of this study, price increases exceeding 100 % within the period 2000-2009 were applied as selection criteria.

Relevance of EEE in metal consumption
Due to the focus of this study on the recovery of metals by the recycling of EEE, the main interest is on metals for which a certain share is contained in EEE and for which EEE therefore represents a potential relevant secondary resource. This criterion would be fulfilled if 10 % or more of the annual global consumption of the specific metal is used for the production of EEE (all EEE products, not only the products assessed in this project)[14]. The rationale of this criterion is to focus on metals for which the recycling of WEEE can contribute in a significant way to the security of supply for this raw material.

In order to be included in this study, a metal must fulfil the criterion "relevance of EEE in metal consumption" and at least two out of three criteria, for each dimension (i.e. 'supply risk' and 'economic relevance' (cf. chapter 2.3). The following tables show the results of the application of these criteria to sixty metals[15]).

Table 2 lists the metals that fulfil the criteria. The assessment is based on data from the U.S. Geological Survey for the reserve-to-production ratio, the regional concentration of reserves and the price developments. The data for the availability of recycling technologies, the demand growth and the relevance of the EEE-related demand is taken from the study conducted by the EU Raw Material Initiative (EU, 2010). These metals in Table 2 can be seen as a 'first choice'.

Table 2: Applying selection criteria for the selection of metals for further investigation

Metal	Supply risks			Economic relevance		
	Reserve-to-production ratio[1]	Regional concentration of reserves[1]	Lack of suitable recycling technologies[2]	Rapid growth in demand[2]	Price development[1]	Relevance of EEE in metal consumption[2]
Silver	X	O	O	X	X	X
Cobalt	O	X	O	X	X	X
Indium	X	X	(X)	X	X	X
Lithium	O	X	O	X	X	X
Tantalum	X	X	X	X	O	X
Tellurium	O	X	X	X	X	X
Tungsten	X	X	O	X	X	X

X: criterion fulfilled; O: criterion not fulfilled. Brackets indicate uncertainty.

[14] Referring to the definition of WEEE in the WEEE Directive, plus batteries, as they are often collected as part of WEEE.

[15] The selection procedure was based on work achieved in Wittmer et al, 2011.

1 cf. USGS, 2008a and USGS, 2011; 2 cf. EU-Commission, 2010

Table 3 lists further metals that fulfil the criteria to a large degree. They could be seen as ‘second choice’.

Table 3: Selection criteria applied for the extended selection of metals for further investigation (optional selection)

Metal	Supply risks			Economic relevance		
	Reserve-to-production ratio[1]	Regional concentration of reserves[1]	Lack of suitable recycling technologies[2]	Rapid growth in demand[2]	Price development[1]	Relevance of EEE in metal consumption[2]
Gold	X	O	O	O	X	X
Beryllium	O	X	X	O	O	X
Gallium	O	?	X	X	O	X
Germanium	O	?	X	X	O	X
Palladium	O	X	O	X	O	X
Ruthenium	O	?	O	O	X	X

X: criterion fulfilled; O: criterion not fulfilled; ?: no data available.
1 cf. USGS, 2008; 2 cf. EU-Commission, 2010

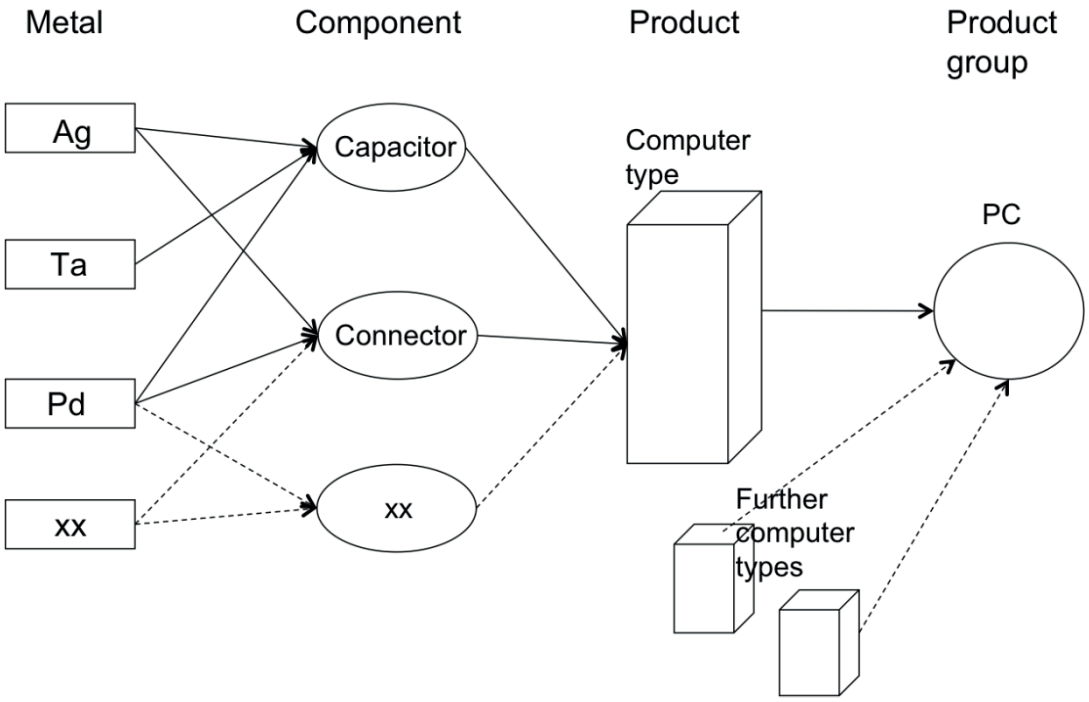
3.3 Methodology on the selection of the product groups and components

3.3.1 The role of components

Critical metals are used in different electronic and electric equipment (EEE) for their specific physical or electro-chemical characteristics, which ultimately provide certain functions for the specific equipment[16]. To trace which product groups and components of EEE are relevant carriers of the selected set of critical metals requires an assessment of the components in which the metals are present. Furthermore, a differentiation of products and product groups is required in order to distinguish the composition of (a) certain product types (e.g. a certain type of computer such as desktop computers), and (b) the corresponding product group (composed of all products belonging to the product group, here: the product group PC). The greatly simplified interrelationships between the metals, components, products, and product groups are illustrated for the PC product group (Figure 3). The arrows indicate which metals are used in the components, which components are used in the product, and which products determine the overall product group 'PC'.

[16] For simplification, similar types of products are grouped as product group (e.g. "PC").

Figure 3: Schematic composition of products/product groups on the example of PC. For clarity, only a share of the PC composition is shown. The dashed arrows indicate additional items not further specified



Note that in some cases the same components are used in different types of EEE; in other cases, the components are equipment-specific (e.g. a specific integrated circuit for a specific type of computer). However, the knowledge base on these interrelationships between the EEE products and the EEE components is currently not sufficient, either within the project team or in the scientific literature. There are single studies that provide information on the metal/material composition of products/product groups but these lack data and are difficult to interpret consistently. Limited knowledge on the overall composition of the products/product groups as well as rapid technological development within the EEE sector offers a further constraint. Therefore this study has focused on selected metals, selected components, and selected product groups in order to stay within manageable bounds and to enable an analysis and reach conclusions based on reasonable evidence.

3.3.2 Critical metals used in components

End-consumers generally do not buy or discard components; in fact, they are seldom aware of their existence when using the products containing them. EEE products require specific components in order to function (cf. Figure 3). In general, these components are used as *intermediate products* for the production of the so-called *end-products*. Although the 'recipes' vary from producer to producer; the 'ingredients' are in many cases rather similar. A consideration of both components and EEE products is necessary in order to answer the questions to be addressed in this study.

The WEEE collection system starts with products as input, thus figures on the potential of recycling volumes and collection rates refer to the product level. However, the metal content is expected to be more homogeneous for the components, therefore, statistics on them are considered to be more meaningful in this respect. The components are characterised by their basic function, while their materialisation is a temporal variable. As such, it depends on the design, the (technical) performance, and the technical type of component (for example, diodes are electronic component that carry electric current in only one direction). Based

on an extensive literature review of critical metals and their applications, we suggest the assessment of the following EEE components:

- Capacitors;
- Integrated Circuit;
- Connectors;
- Wiring;
- Diodes;
- LED;
- LCD;
- Thin films (to be separated into different types);
- Optical electronics (optical fibre camera lenses etc.);
- Rechargeable batteries (those types, which are contained in the WEEE/selected WEEE product groups), e.g. lithium batteries and different battery types containing cobalt[17].

3.4 Selection of EEE product groups

In general terms, the selection of the specific product groups is based on:

a) The material significance – by the share of the physical volumes (annual use) of the metals, which is covered by them;
b) The economic significance – by the annual sale volumes (monetary turnover) of the product groups;
c) The expected data availability – evaluated based on expert judgement.

The project team evaluated the different product groups with regard to the presence of 'critical metals' and the economic significance of the product group.

The economic significance was evaluated by a basic screening of economic figures of the product groups. Based on this evaluation, the following product groups are suggested for assessment:

a) Mobile phones;
b) Personal Computers (desktop computers);
c) Laptops and notebooks;
d) TV and flat screen monitors;
e) Thin film and conventional crystalline solar power converters (photovoltaic cells);
f) Rechargeable batteries (as contained in WEEE).

Table 4 shows the use of the critical metals, on which this study focuses.

[17] All other batteries are neglected.

Table 4: Use of the listed critical metals

Metal	Mobile phones	PC	Flat screen TVs and monitors	Solar power converters	Rechargeable batteries	Notebooks/ Laptops
Cobalt	+(a)		+		+	+(a)
Indium	+	+	+	+	+	+
Lithium	+(a)		+		+	+(a)
Silver	+	+	+	+	+	+
Tantalum	+[18]		+	+		+
Tellurium		(+)		+		
Tungsten	+[19]	(+)	+			
Gold	+	+	+			+
Beryllium	+	+				+
Gallium	+	+	+	+		+
Germanium	+	+		+		+
Palladium	+	+	+			+
Ruthenium		+	+			+

(a) = within batteries

3.5 Methods used to measure the metal content

The calculations of the metal contents in the selected EEE products and their components are based on extensive literature reviews. As metal contents do not significantly differ between different regional markets, studies from Europe and especially from Japan have been taken into account: Chancerel 2010; MOE & METI 2010; JOGMEC 2008; Kida, Shirahase and Kawaguchi 2009; Central Council on the Environment 2011; Oguchi et al. 2011; Oguchi 2007. Technical information regarding the different methodologies of the Japanese analysis can be found in Annex II.

[18] http://ecadigitallibrary.com/pdf/CARTSASIA06/4_4%20Pelcak-AVX.pdf

[19] Tungsten has specific use in mobile phones in that it is used for the vibrating function of mobile phones
http://theblogpaper.co.uk/article/mulondon/politics/10jun10/what-wrong-mobile-phones

4 Actual and potential collection of WEEE

In this chapter we present data on the current collection of the selected WEEE product groups, and projections for the future generation of waste of these products.

4.1 Existing collection and recycling of WEEE is too low

In 2007, the total amount of WEEE reported as separately collected in the EU-27 was quite low compared with initial expectations when the WEEE Directive was originally implemented (Eurostat, 2011). In 2007, 2.2 million tonnes were reported as separately collected compared to an expected generation of over 7 million tonnes (United Nations University, 2007). In 2008, 3.1 million tonnes of WEEE was collected; still much lower than expected. Moreover, only 2.6 million tonnes of the collected WEEE underwent treatment[20].

Three major weaknesses can explain why the present total amount of recycled WEEE and of associated critical metals remains low. The two first factors affect WEEE in general, whereas the last one is specific to the recycling of critical metals:

1. The collection rate for WEEE in the EU is insufficient.
2. Too much WEEE is exported (legally and illegally) from the EU as used products.
3. The recovery rate from end-processing of WEEE is insufficient for some of the metals as the recycling process (dismantling, pre-processing, end-processing) focuses on and is tailored to extracting bulk materials, and satisfying end-processing technologies are missing. This is partly because thermodynamics limit the technical recyclability of certain metals if they are alloyed in complex mixes with other elements. (Gößling-Reisemann, S., 2008).

The recycling of solar panels is subject to special conditions, meaning that the missing recycling of this waste type cannot be linked to these three factors. While solar panels have been used for several years, the long working life of the panels means that only very few have reached end of life. Consequently, solar panels represent a potentially significant future waste stream. Different technologies of solar panels exist, with each containing different types and amounts of critical metals.

Some sources claim that the true collection (and recycling) rate of WEEE is much higher than the amount reported by Member States (Finland, 2011; Germany, 2011; Netherlands, 2012 and WRAP, 2011). Member States are required to report on WEEE that has been separately collected for reuse or treatment and recycling. The reporting shall cover what is collected from private households and what is collected from other than households. The reporting is normally based on the flows reported under the national systems set up to implement the WEEE Directive. There are several reasons why the reported figures may not reflect the full extent of WEEE collection and processing, these include:

- Some WEEE will be collected and processed through the secondary metals industry outside of the collection systems set-up for WEEE. This is often the case for large kitchen appliances such as dishwashers and cookers that have a high metal content and do not contain hazardous components requiring specialist treatment. These items by weight account for a very large proportion of the total amount of EEE placed on the market and the amount of WEEE produced. These items will usually be processed via

[20] These figures are for all WEEE, not only those containing critical metals.

shredders that would also have been used had the equipment been separately collected through the WEEE system. Therefore, the equipment is being treated appropriately but the data associated with it is not being captured for the purpose of reporting collection and recycling for the purposes of the WEEE Directive.

- A significant amount of non-household equipment is taken back directly by producers who have their own arrangements for dealing with it. Not all of these arrangements are reported to Producer Compliance Schemes and Regulators and, therefore are not captured in the national statistics.

Currently, a significant proportion of WEEE continues to be disposed of with mixed waste because, for example, householders do not always choose to use the WEEE take-back systems available to them. In the Netherlands 2.2 kg of WEEE per capita found its way into mixed waste in 2010 (Netherlands, 2012).

The recent recast of the WEEE Directive will lead to higher collection and recycling targets, the removal of the distinction between household and non-household WEEE and further measures to combat illegal exports. These changes are expected to lead to more WEEE being collected, processed and recorded through the official WEEE systems.

This report uses the official amounts reported to the Commission (Eurostat).

4.2 Amount of collected WEEE in 2007 and 2008 related to the selected product groups identified as containing critical metals

Table 39 in Annex III shows that, of the WEEE collected in 2007 and 2008, large household appliances (category 1 of the WEEE Directive (EU-Commission, 2002)), IT & Telecommunication (category 3) and Consumer equipment (category 4) represent the largest share.

Relatively high collection rates are characteristic of product groups large in physical size, contain significant amounts of bulk materials, or are rich in content of valuable metals; characteristics of large household appliances, IT and telecom or consumer equipment.

These features are likely to provide strong economic incentives for recycling. Other groups with closely related properties (e.g. medical equipment) are subject to much lower collection rates, which could be a result of their high value on the second hand market.

As shown in Table 5, the selected products groups for this study either belong to categories 3 or 4 of the WEEE Directive (EU-Commission, 2002) or are not included in any WEEE category.

Table 5: The WEEE categories related to the selected product groups of the study

Product type	WEEE category	Product type	WEEE category
Mobile phones	3	Total solar photovoltaic waste	No EU classification
PCs	3	Thin film solar power converter	No EU classification
Desktop personal computer	3	*Cadmiumtelleruide (CdTe)*	No EU classification
Laptop/Netbook/Tablet	3	*Copper-Indium-Selenide (CIS)*	No EU classification
Flatscreen monitors	4	*Copper-Indium-Gallium-Diselenide (CIGS)*	No EU classification
LCD TV	4	*Amorphous (non-chrystalline) silicon*	No EU classification
LCD Monitor	4	Thick film solar power conwerter	
Plasma TV	4	*Monocrystaline silicon*	No EU classification
Rechargeable batteries in WEEE	In principle all	*Polycrystaline silicon*	No EU classification

Source: Based on (EU-Commission, 2002)

In order to estimate the amount of collected mobile phones, PCs and flat panel displays collected in EU-27, it is necessary to estimate the fractions of WEEE category 3 and 4 in Table 39 in Annex III corresponding to these product groups. However, there is no existing EU data regarding this rate. The best existing available data covers Germany for 2007 (Chancerel, 2010) and even these data do not cover all product types.

The results of the calculations are shown in Table 6 and Table 7. Table 6 estimates the collected amounts of Laptops/Notebooks/Notepads, LCD TV, LCD monitor and Plasma TV in Germany for 2007. A key assumption in the following calculation of generated waste is that an identical percentage of these product groups can be found in both the waste generation of category "Large high-grade equipment" (as defined in Chancerel, 2010) and the waste collection of the same category.

Table 6 Calculation of collected waste amounts of specific product groups in Germany in 2007, in tonnes

Product Group	WEEE Category	Generation of product group (DE) in 2007, tonnes	Generation of category "Large high-grade eq." (DE) in 2007, tonnes	% of product group in generated category "Large high-grade eq."	Collected "Large high-grade eq." (DE) in 2007, tonnes	Collected product group (DE) in 2007, tonnes
Laptop/ Notebook/ Notepad	3	3 978	87 071	4.57 %	44 339	2 026
LCD TV	4	5 908	87 071	6.79 %	44 339	3 009
LCD monitor	4	4 127	87 071	4.74 %	44 339	2 102
Plasma TV	4	0	87 071	0 %	44 339	

Source: Own calculation based on (Chancerel, 2010). * Plasma TV sets were brought on the market in the late nineties and they were very expensive. In a Swiss study (SWICO, 2011) it is assessed that plasma TV sets cover one to five per cent of the monitor market in Switzerland in the period from 2007 to 2030 (SWICO Recycling, 2011). Therefore we assume in this paper that the waste generation of plasma TV sets can be disregarded.

Table **7**Table 7 estimates the collected amount of the selected product groups at a European level. In this case, it is assumed that the proportion of the WEEE categories accounted for by the product groups of interest is the same across the EU as in Germany.

Table 7: Calculation of collected waste amounts of the selected product groups in EU in 2007 and 2008, in tonnes

Product Group	WEEE Cate-gory	Collected amount of product group (DE) in tonnes, 2007 (b)	Collected amount of WEEE category (DE) in tonnes, 2007(c)	Collected product group/ Collected WEEE category (DE) in %, 2007	Collected amount of WEEE category (EU) in tonnes, 2007(c)	Collected amount of WEEE category (EU) in tonnes, 2008(c)	Collected amount of product group (EU) in tonnes, 2007	Collected amount of product group (EU) in tonnes, 2008
Mobile Phones(a)	3	240	117 749	0.20 %	390 291	575 976	796	1 174
Desktop Computer	3	9 948	117 749	8.45 %	390 291	575 976	32 974	48 661
Laptop/ Notebook/ Note-pad(a)	3	2 026	117 749	1,72 %	390 291	575 976	6 715	9 910
LCD TV	4	3 009	130 620	2.30 %	343 285	442 746	7 908	10 199
LCD moni-tor	4	2 102	130 620	1,61 %	343 285	442 746	5 524	7 125
Plasma TV(d)	4	0	130 620	0	343 285	442 746	0	0

Note: (a): Inc. original battery
Source: (b) Own calculation based on (Chancerel, 2010), (c) (Eurostat, 2011) and (d) (SWICO Recycling, 2011)

4.2.1 Amount of collected solar photovoltaic waste in 2010

Photovoltaic (PV) modules are considered a rather new technology with lifetimes of around 30 years. Therefore, collection and recycling infrastructures are not yet fully developed. The fact that PV modules were not regulated under the old WEEE Directive, but they are under the new one (EU-Commission, 2012), could also contribute to the current recycling situation. The industry has established its own take-back system called PV Cycle. They have more than 200 members representing more than 90 % of the PV industry. Since June 2010, PV Cycle has established more than 150 collection points in 11 EU member states where they take back end-of-life PV. In 2010, PV Cycle collected 615 tonnes of PV modules for recycling.

One example of a private industrial facility for collecting PV modules in Europe is *First Soler*, which recycled 1 900 tonnes of PV modules in 2010. These were, however, CdTe-Thinfilm modules returned under a manufacturer call-back due to a manufacturing error and are considered to be new scrap rather than an end-of-life product. As such, they are not included in this study.

Therefore, the collected amount of end-of-life PV modules is assumed to be 615 tonnes in 2010 and about 1 350 tonnes in 2011 (PV Cycle, 2011).

4.2.2 Amount of collected rechargeable batteries in WEEE

Information on the collected amounts of Li-Ion and NiMH types of rechargeable batteries in Germany in 2009 can be found in a recent UBA report (UBA, Germany, 2011). According to that report, 634 tonnes was collected in Germany. This can be extrapolated to cover the EU based on GDP, giving 3 009 tonnes of collected batteries in 2009. Since other sources only can give information about the total amount of collected rechargeable batteries

in Europe, this figure (3 009 tonnes) is used in the report. The amount of rechargeable batteries covers only batteries used in the selected product groups.

4.3 Assessment of the potential future amount of WEEE

4.3.1 Description of the calculation model(s) developed for the assessment

To estimate the current and future generation of WEEE related to the selected product groups, a model has been constructed based on the sales of the selected products and their anticipated life span.

The number of products put on the market is combined with a lifetime distribution to calculate waste generation. A lifetime distribution is preferred over an average life span since it provides more detailed information: the products purchased in a given year will not all become waste at the same time; instead, some of these products will become waste in the same year, some others in the following year, some others in the year next, etc. This lifetime distribution is unique for each product and is presented in chapter 4.3.3.

4.3.2 Identify the amounts/units put on the market of the selected products

To take advantage of product lifetime distribution, it is necessary to use a time series for the sale of the corresponding EEE products, solar panels and rechargeable batteries. The lifetime distribution assumes that, at least in some cases, some of the products purchased in a given year would become waste more than 10 years later. Therefore, in order to estimate the waste generation in 2010, sales data should exist for the years before 2000. In fact, in order to compare this calculated waste generation with the official Eurostat data for collected WEEE, the waste generation calculations should include the years 2006, 2007 and 2008.

Mobile Phones

Eurostat's Prodcom database contains data on imported and exported goods as well as goods produced in the EU. Code 26302200 refers to "Telephones for cellular networks or for other wireless networks" and is selected to represent the product 'mobile phones' in this report. At the time of calculation (July 2011) data in Prodcom only cover the years 2007, 2008 and 2009. The values in the Prodcom database are expressed in units of products sold. In order to convert these into weight units, the average weight of a mobile phone is used. By using Nokia as a proxy, the weight of a mobile phone can be seen as having fluctuated both above and below this value since 1994 with the development of increasingly lighter models and more recently with heavier smartphones. We calculated that to be an average weight of 152 g for the entire period of the investigation (1999-2010).

In order to create a time series for mobile phone sales in the EU, back-casting (extrapolation) is required. This back-casting is based on the EU's GDP developments and data from individual countries. The back-casting based on GDP would not be robust enough if based solely on the sales figures from only three years. Therefore a longer data series is constructed based on the national sales figures from Germany and Portugal.

In Germany, the official WEEE register contains data on the sale of mobile phones to consumers from 2006 to 2010 (EAR, 2011). However, there is no data on the amount of mobile phones sold to businesses. In order to account for this part of sales as well, the ratio between all products included in category 3 of the WEEE Directive (EU-Commission, 2002) sold to consumers and to businesses is used. Using this ratio, the consumer sales of mobile phones is up-scaled to include all sales in Germany for the period 2006-2010.

On the other hand, the Portuguese EEE register includes detailed national data for the years 2007, 2008 and 2010 (Anreee, 2011).

In order to extrapolate the national German and Portuguese figures into data for the entire EU, GDP data is used. The results of the extrapolation show similar figures to Prodcom for the years 2007 and 2009. The Prodcom database for 2008 includes a very low number for mobile phones sales (43 % lower than the 2007 or 2009 values), which cannot be fully attributed to the beginning of the economic downturn. Therefore, the extrapolation figure is used instead for 2008.

The extrapolation results, together with Prodcom data, constitute a database of five years (2006-2010). This basis is used to back-cast the sales data until 1999 using the development in EU GDP. This back-casting might overestimate the sales in earlier years since they depend more on the specific technology's penetration to the market and consumer habits than GDP. Table 8 presents the results of these calculations.

Table 8 Estimated mobile phones sales in the EU from 1999 to 2010 (in tonnes)

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Tonnes sold	38 849	40 351	41 149	41 656	42 206	43 270	44 114	45 554	50 615	47 472	50 424	40 535
Source	back-casting	back-casting	back-casting	back-casting	back-casting	back-casting	back-casting	DE	Prodcom	DE, PT	Prodcom	DE, PT

Note: The main objective of this task is to estimate the waste generation in 2015. As such, it has been decided use the most recent sales data point (2010) for the years 2011-2015.

Computers

The Prodcom database has separate information on sold items for laptops and desktop computers. Codes 26201100 – "Laptop PCs and palm-top organisers" and 26201300 – "Desktop PCs" are used in this report. The data cover the years 2007, 2008 and 2009, but the figures in 2007 are not used: for laptop computers, the 2007 figure is very low (about 10 % of the 2008 value) and for desktop computers, the sum of imports and local production is lower than the exports for 2007.

In order to convert the Prodcom figures from items to weight units, the average weights of a laptop and a desktop computer are used: 2.815 kg and 12.154 kg respectively (Chancerel, 2010).

Data covering only two years is not enough for back-casting, so national data from Germany and Portugal is used.

Gesellschaft fűr Unterhaltungs- und Kommunikationselektronik (GFU) provides a consumer electronic market index report where data on laptop and desktop computers sold to consumers in Germany are found (GFU, 2011). This data covers the years between 2005 and 2010. The ratio between sales to consumers and businesses from 2009 is used to obtain national total sales figures, as in the case of mobile phones.

The Portuguese EEE register contains sales data for laptops, desktops, notebooks and notepads in the years 2007, 2008 and 2010. Notebooks and notepads are grouped together with laptop computers.

The national data are extrapolated to the EU figures using GDP, as in the mobile phones case. This extrapolation gives similar values as the Prodcom database, although the Prodcom numbers themselves differ a lot in the two reporting years. The time series constructed extends from 2005 to 2010. The back-casting is estimated on the basis of the GDP until 1995 for desktop computers and until 1999 for laptops. This is done because laptops were

not a popular market commodity before 1999, so we assume that no laptops were sold before this date in order not to overestimate the sales and subsequently the waste generation. Table 9 presents the results of these calculations.

Table 9 Estimated computers' sales in the EU from 1995 to 2010 (in tonnes)

Year	1995	1996	1997	1998	1999	2000	2001	2002
Laptops	0	0	0	0	35 448	36 818	37 546	38 009
Desk-tops	117 405	119 539	122 793	126 443	130 307	135 345	138 020	139 723
Source	back-casting	back-casting	back-casting	back-casting	back-casting	back-casting	back-casting	back-casting

Year	2003	2004	2005	2006	2007	2008	2009	2010
Laptops	38 511	39 481	40 251	47 137	68 431	163 261	150 105	154 163
Desk-tops	141 568	145 135	147 965	129 430	134 764	256 908	107 557	149 161
Source	back-casting	back-casting	DE	DE	DE, PT	Eurostat	Eurostat	DE, PT

Note: The main objective of this task is to estimate the waste generation in 2015. As such, it has been decided use the most recent sales data point (2010) for the years 2011-2015.

Flat Screens

The flat screens category mainly includes LCD and some Plasma TV sets. Other technologies, such as LED TV sets, are excluded as until very recently their market penetration was limited and no reliable indicators exist to enable the generation of sales forecasts. Computer monitors are also not included in this category as they are already accounted for in the desktop computers analysis referred to in the above table. However, the computer analysis includes only monitors sold together with a desktop computer. There are a certain number of monitors that are sold separately which should be included in the flat screens category if possible, however there is no information available on the significance of these sales. No allowance has been made for flat screen monitors that may have been sold separately.

The Prodcom database includes data on the sales of flat monitors and screens in the EU, under the code 26403460 – "Flat panel video monitor, LCD or plasma, etc., without tuner (colour video monitors) (excluding with cathode-ray tube)". However, it is unclear whether the Prodcom figures refer to monitors only or both monitors and TV sets. In order to examine this issue, the Prodcom data are compared to extrapolations from national figures with the use of the national /EU GDP figures.

GFU in Germany offers market index reports for consumer electronics in Germany (GFU, 2011). These reports include sales data for both LCD and Plasma TV sets for the years 2005 to 2010 to consumers. The ratio between sales to consumers and businesses from 2010 is used to obtain national total sales figures, as in the case of mobile phones.

Moreover, the Portuguese register ANREEE contains data on TV sets sold in 2007, 2008 and 2010. These figures also include some TV sets with cathode ray tube (CRT) technology, although it is not possible to obtain the figures for flat screens separately. However, the CRT TV sets sales are expected to be very low and can therefore be disregarded.

The Danish Association of Consumer Electronic Providers publishes data on the sales of flat screens, including both LCD and plasma models together, in the Danish market from 2002 to 2009 (BFE, 2011).

By extrapolating these national data to an EU level from each country separately, all obtained results deviate greatly from the Prodcom figures. Therefore, the Prodcom figures are not used in this analysis since they might be referring to flat monitors only and not TV sets. Instead, all national extrapolations are used and when there is more than one country's data available, a weighting between the extrapolations is performed, based again on the national GDP.

The extrapolated data are converted into weight units, using the average TV set - LCD-Monitor's weight of 8.6 kg (Chancerel, 2010). This data covers the time period from 2001 to 2010. The 2001 figure is based only on Danish data and claims that there were no flat screens sold in that year. Therefore, there is no back-casting necessary since it is reasonable to assume that no sales of flat screens occurred before 2001, as CRT technology was dominating the market before that. Table 10 presents the results of these calculations.

Table 10 Estimated flat screens' sales in the EU from 2000 to 2010 (in tonnes)

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Flat Screens	0	0	559	9 395	28 248	66 707	135 470	211 686	296 229	351 223	385 255
Source	As-sump-tion	DK	DK	DK	DK	DE, DK	DE, DK	DE, DK, PT	DE, DK, PT	DE, DK	DE, PT

Note: The main objective of this task is to estimate the waste generation in 2015. As such, it has been decided use the most recent sales data point (2010) for the years 2011-2015.

Rechargeable batteries
Information is published in the EPBA Sustainability report on units of rechargeable batteries consumed per capita in Europe in 2009. However, this data cannot be used for the purpose of this report since they refer to all typ es of rechargeable batteries and it is not possible to extract the weight of batteries consumed.

4.3.3 Identify/estimate the average lifetime of the selected products or the distribution of the lifetime

As mentioned previously, we use a lifetime distribution instead of an average life span in order to estimate when one of the selected products becomes waste if purchased in a given year. This choice increases the accuracy of the modelling compared to the uncertainty caused by estimating average life spans.

A Nordic Council of Ministers report from 2009 (Nordic Council, 2009) includes a relevant lifetime distribution, based on questionnaires to experts in the EEE field. The calculated lifetime distributions for the products selected in this report are shown in Table 11 below. The percentage figures refer to the part of the products purchased in 'Year 0' that becomes waste in the same or following years.

Table 11 Estimated lifetime distribution for the selected products in % of sold items in Year 0

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Mobile phones	2.9	6.0	22.7	30.9	23.4	10.7	2.9	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Laptops	0.0	2.9	10.6	17.4	20.4	18.8	14.1	8.7	4.5	1.9	0.7	0.2	0.0	0.0	0.0	0.0	0.0	0.0

Desktops	0.7	1.8	8.2	15.3	19.9	19.9	15.8	10.2	5.2	2.1	0.7	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Flat screens	1.0	1.4	5.1	9.1	12.3	14.0	14.1	12.8	10.4	7.8	5.3	3.3	1.8	1.0	0.4	0.2	0.1	0.0

Source: Nordic Council of Ministers report from 2009 (Nordic Council, 2009)

The figures in Table 11 allow the estimation of waste generation of the selected products in all of the years following their purchase. In order to compare with the WEEE collection data reported in Eurostat, the waste generation must be calculated from 2006 onwards. This means that the data requirements for product-group sales figures are as follows:

- Mobile phone from 1999 onward (seven years before 2006 – the last 0.5 % of the phones sold in 1999 will become waste in 2006),
- Computers (laptops and desktops) from 1995 onward and (eleven years before 2006 – the last 0.2 % of the laptops and desktop computers sold in 1995 will become waste in 2006)
- Flat screens from 1990 onward (sixteen years before 2006 – the last 0.1 % of the flat screens sold in 1990 will become waste in 2006).

Regarding Photovoltaic (PV) modules, it is difficult to assess their average life span or lifetime distribution since it is a relatively new technology and there has not been very much waste generated so far. The technical warranty for modules is 25 years but two recent reports claim that the actual life span could very well be between 30 and 40 years (Bio Intelligence Service, 2011; PV Cycle, 2011).

4.3.4 Estimate the potential generated amounts of WEEE, solar panels and batteries related to the selected products in the period 2006-2015n

Mobile phones, Computers and Flat screens

Based on the quantities sold in the EU (chapter 4.3.2) and the lifetime distribution (chapter 4.3.3) of the selected products, it is possible to estimate their waste generation from 2006.

The time series of the sold quantities allows for waste generation estimation only until 2010, which is the last year of existing sales data (with the exception of flat screens as mentioned above). Given that the scope of this study extends to 2015, the forecasting of waste generation is required. However, since the selected products are highly dependent on rapid technological and lifestyle changes, it is not possible or useful to forecast the sales data to 2015. On the other hand, the main objective is to estimate the waste generation in 2015, therefore it has been decided to keep the sales stable and equal to the last year of existing data (2010). In this way, an approximation of the potential generated waste could be obtained for the years 2011-2015.

The collection of flat screens also includes computer monitors. In order to be able to compare the generated waste amount of flat screens and the collected amount, it is necessary to allocate the weight of waste computer monitors to the flat screens category. By then comparing the two figures, it is possible to assess the level of losses for flat screens due to insufficient collection. In Table 12, the weight of the screens (approximately 4.5 kg per item) is subtracted from the 'desktops' category and added to the 'flat screens' category.

The table below shows the estimated waste quantities of the selected products for the years 2006 to 2015.

Table 12 Estimated waste generation for the selected products in tonnes, in the EU, 2006-2015

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Mobile phones (ex. Batteries)	32 674	33 420	34 289	35 694	36 621	36 987	35 844	33 879	32 286	31 523
Mobile phones-batteries (incl. spares)	12 091	12 368	12 689	13 209	13 552	13 687	13 265	12 537	11 948	11 666
Laptops (ex. Batteries)	30 148	32 255	34 518	40 491	53 549	71 646	91 022	107 759	119 693	126 775
Laptop batter-ies (incl. spares)	6 242	6 678	7 147	8 383	11 087	14 834	18 845	22 310	24 781	26 247
Desktops	86 466	87 996	89 166	89 652	93 587	97 073	99 297	99 385	97 827	95 973
Flat screens	55 489	62 955	76 197	97 048	129 409	170 232	216 646	263 902	307 999	346 363
Total	**223 110**	**235 672**	**254 006**	**284 477**	**337 805**	**404 459**	**474 919**	**539 772**	**594 534**	**638 547**

Source: Own estimation based on the quantities sold of the selected products (Table 8-Table 10) and the lifetime distribution of the products (Table 11)

PV Modules

Assessing the amount of end-of-life solar photovoltaic products is complicated as no existing figures cover 2007 or 2008. The earliest figures cover 2010 and there is no agreement between the sources regarding the generated amount.

Three different reports and approaches calculate the waste of photovoltaic modules at a European level. The first one published in 2007, was conducted by Ökopol GmbH (Ökopol, 2007) and calculated the amount to be approximately 8 000 tonnes in 2010. Another source is PV Cycle (PV Cycle, 2011), which started its first collection points in June 2010 and opened 87 collection points in nine different countries across Europe. Bio Intelligence has assessed the generated amounts of photovoltaic modules but the first year including data is with approximately 22 700 tonnes of which 17 200 tonnes are based on the first generation of technology (Thick film).

One of the most important assumptions to be made is the average life time of photovoltaic modules. Bio Intelligence Service has estimated the lifetime to be at least 25 years. Bio Intelligence Service has stressed that this only represents the warranty and not the technical lifetime, which can be as long as 30 or 40 years (Bio Intelligence Service, 2011).

According to two more recent studies (Bio Intelligence Service, 2011; PV Cycle, 2011), in 2025 the first generation of PV modules, based on crystalline silicon, will dominate the waste generation. Therefore, it is assumed that within the time scope of this study, only first generation PV modules will have become waste.

Table 13 includes estimates for PV waste generated. The information is based on PV Cycle.

Table 13 Quantities of PV waste

Year	2010	2011	2012	2013	2014	2015	2016	2017
	500	700	900	900	900	900	900	1 040

Sources: PV Cycle 2011,

In order to create a forecast for the generation of PV modules, an average is taken between Ökopol and PV Cycle predictions until 2015.

Rechargeable Batteries

The rechargeable batteries are sold both as part of electronic products and separately as spare parts.

Rechargeable batteries are contained in two of the selected product groups: laptops and mobile phones. The weight of sold products includes the weight of their batteries. This report uses product-specific average weights for the batteries which allow an estimation of the amount of waste batteries based on the estimations for the products. The weights for the battery packages are based on a study by USGS (2008): 22 g for mobile phones and 280 g for laptops.

Batteries are also bought as spare parts. In order to estimate this quantity, it is assumed that 25 % of laptops or mobile phones will require replacement batteries during their life span. As such, the total amount of batteries associated with sold laptops and mobile phones is calculated to be 25 % more than that included in new products.

The calculated weight of waste rechargeable batteries based on this methodology is shown in Table 12 above.

Table 14 compares the amount of collected waste products for 2007 and 2008 calculated in Chapter 4.2to the amount of generated waste products as estimated in this chapter. This comparison allows an assessment of the losses of critical metals due to the insufficient collection of relevant WEEE products. The relation between generated and collected amounts is an outcome of multiple assumptions so the result is subject to high uncertainty. However, Table 14 gives a good indication of the size of the losses due to insufficient collections.

Table 14 Generated and collected amounts of selected products in tonnes, in the EU, 2007-2008

Year	2007			2008		
	Generated amount (tonnes)	Collected amount (tonnes)	Collected/ Gener-ated (%)	Generated amount (tonnes)	Collected amount (tonnes)	Collected/ Generated (%)
Mobile Phones (2008)	43 314 (a)	796 (a)	2.38	44 440 (a)	1 174 (a)	2,64
Laptops (2008)	37 597 (a)	6 715 (a)	16.42	40 235 (a)	9 910 (a)	24.63
Desktops (2008)	87 996	32 974	37.47	89 166	48 661	54.57
Flat Screens[21] (2008)	62 955	13 432	21.34	76 197	17 324	22.74
PV Modules (2010)				4 137	615	14.87
Batteries (2009)				21 592 (b, c)	3 009 (b, c)	13.94
Total	221 968	53 377	24.05	265 616 (b)	80 693 (b)	30.08

Source: Own estimation based on the quantities sold of the selected products (Table 8-Table 10), the lifetime distribution of the products (Table 11) and the collected amounts (Table 7)

(a) Amount incl. original batteries.
(b) This figure will include double counting of batteries in mobile phones and laptops as they are included in the respective rows above.
(c) 2009 figure is used.

[21] Plasma TVs are missing from the collected amounts.

4.4 The amount of WEEE exported from the EU as used goods

According to the EU Waste Shipment Regulation (EU Regulation 1013/2006), WEEE has, in general, to be notified to the authorities before being shipped out of the EU. Every year EU Member States must report shipments of notified waste to the Basel Convention Secretariat and to the European Commission. In general, export of WEEE to non-OECD countries is prohibited, whereas the export of used but fully functional equipment to non-OECD countries is permitted.

However, it is difficult to monitor shipments of WEEE both within and outside the EU. The WEEE fractions do not have a specific code when reporting to the Commission and tend to be assigned ambiguous codes when reported. This implies that the reporting cannot be used to inform about actual WEEE shipments.

The European Environment Agency (EEA) and its Topic Centre on Sustainable Consumption and Production has, in a report (EEA, 2012), evaluated the amount of notified shipments of WEEE in 2007 based on its own survey (ETC/SCP, 2010). The amount of notified WEEE was around 104 000 tonnes in 2007.

Surprisingly, this figure constitutes only a small amount of the generated and collected WEEE. One explanation for this is that some WEEE leaves the EU registered as used products rather than WEEE. Used, but working products do not require notification before shipment and can legitimately be shipped to Asia and Africa. However, these old products are not always fully functional or end up after a short time as WEEE. Much of what should have been registered as WEEE seems to be exported out of the EU disguised as old or second hand products and therefore goes unregistered. The EEA report has assessed (based on studies undertaken by the German Environment Agency and The Danish Environment Agency) that the amount of used electrical and electronic products or WEEE illegally shipped from the EU to non-OECD countries is at least 500 000 - 1 300 000 tonnes per year.

A study conducted by the German Environment Agency includes estimates of the exported used EEE goods related to products groups.

Table 15 Composition of exported EEE goods from Germany in 2008

	Variants of the volume distribution		
	High CRT share	High share of small appliances and PCs	Average share
Type of appliance			
Refrigerators and freezers	10 %	10 %	10 %
Monitors	35 %	30 %	33 %
Televisions	43 %	33 %	38 %
Brown goods	5 %	5 %	5 %
Small appliances	3 %	10 %	7 %
Computers	4 %	12 %	8 %
Total	**100 %**	**100 %**	**100 %**

Source: UBA, 2010

The export of used televisions and monitors out of the EU is assessed to be related to CRT screens. In the future it must be expected that used LCD monitors will also be exported out of the EU. Small appliances stated in Table 15 include mobile phones but it is not possible to say what proportion. It is assumed that the computers are comparable to personal desktop computers, cf. Table 15.

Applying the “high CRT share” scenario to the total amount of illegally exported WEEE (300 000 - 500 000 tonnes per year) a minimum of 12 000 tonnes of used computers are exported each year.

Assuming that the currently exported quantities of CRT monitors and TVs will be replaced by the equivalent quantity of LCD based monitors and TVs over the next 10 to 15 years[22], then the quantity of waste within product groups addressed in this report containing critical metals that is illegally exported out of the EU will increase to over 246 000 tonnes (82 % of 300 000) per year.

[22] This assumption assumes equivalent weight per unit of CRT and LCD monitors.

5 Estimating the efficiency of the entire recycling chain (collection, pre-processing, end-processing)

5.1 Technologies for dismantling and pre-processing of WEEE

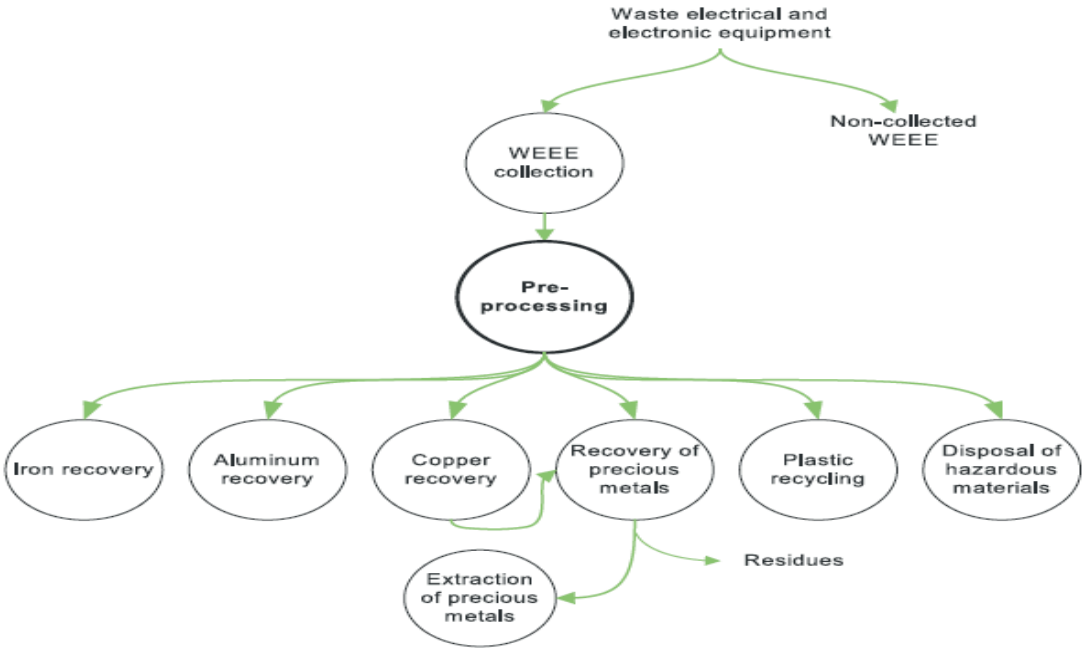
The aim of WEEE pre-processing[23] is the removal of hazardous and valuable components. This can be done manually or automatically before, during or after waste treatment. Although required by law, commonly not all hazardous and valuable components in Annex II of the WEEE directive (EU-Commission, 2002) are removed. The aim is to generate material streams that can go to the correct end-processing for final metal recovery (cf.

[23] In the following, “pre-processing“ stands for “dismantling and pre-processing“

Figure 4:). The comminution stages liberate the feed materials so that the downstream sizing and sorting stages can remove saleable clean fractions based on physical criteria. The system must therefore be able to reduce feed pieces to the required size, break down composites and isolate materials (Drechsler 2006). In order to maximize critical metal yields, the critical metals contained in WEEE must be concentrated in those fractions which enter end-processing facilities capable of recovering these metals.

Common pre-processing processes are liberation and sorting techniques such as manual dismantling, crushing, shredding and automated sorting. Pre-processing takes place at a regional or national level with various facilities all over EU-27. The technique applied largely depends on labour costs and has a major influence on further separation steps and thus on metal recovery efficiencies (Chancerel 2010). Many technologies for automatic size reduction are available on the market.

Figure 4: Simplified recycling chain for WEEE, focusing on recovery of precious metals in the "End-of-Life" and the "Raw materials production" phases (Chancerel 2009)



Cutting systems
Conventional machines that are based on cutting systems are less suitable for WEEE as they generally do not break down material composites but merely reduce their size. They are also highly susceptible to damage from the single solid components frequently contained in the feed material. For processing of WEEE therefore, it is necessary to combine them with comminution machines with other principles (Drechsler 2006).

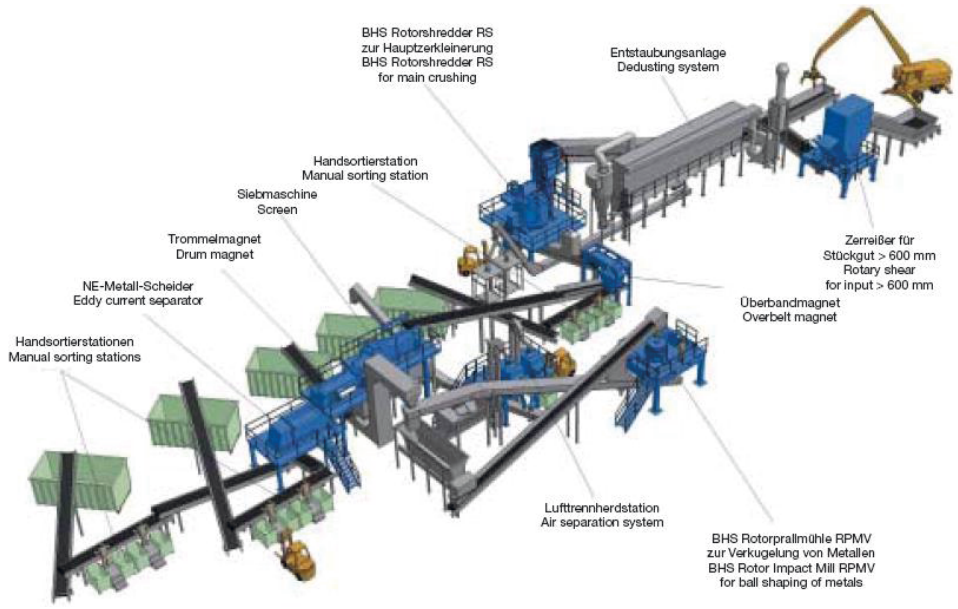
Rotor shredders
Rotor shredders are often used in the first stage to optimize the sizing and sorting behaviour of WEEE in the downstream process stages. Inside of the machine a vertical rotor rotates with flexibly mounted tools that are aligned by centrifugal force during operation of the shredder. Brittle materials are comminuted by impact; composite materials are broken down by shear force. The result is a material mix of defined maximum size in which the metals and other mass materials are partly liberated.

For WEEE, the system can be specified to liberate small components containing harmful substances and critical metals without destroying these. However, there are still limits. These shredders still operate with impact and brittle components (e.g. ceramic) can be broken. Rotor shredders are rather useful to 'break open' bigger devices (such as a copier machine or a PC), so that afterwards components (e.g. circuit boards, batteries, disc drives) can be removed largely intact. But they are not appropriate to really liberate small components (e.g. a tantalum capacitor).

Rotor impact mill
In order to process materials with a size of less than 20mm and to improve the economic profitability and efficiency of the recycling process, these parts are often fed to rotor impact mills where the remaining metal-plastic composites are broken down and the metals themselves are present in a round or pelletized particle shape. Pre-comminuted circuit boards

are broken down based on separation of the materials from circuit board substrates by shearing and friction. Figure 5 shows a possible combination of these technologies.

Figure 5: Pre-processing in a WEEE recycling plant (Drechsler 2006)



Hammer mill
An alternative to this combined system are vertical hammer mills where the material is dropped into the mill at the top and falls down to the milling area. The milling area consists of a rotor and several different milling levels consisting of several so-called ring hammers. The material falls through the mill from the very top to the bottom and is beaten by the hammers against the housing of the mill (cf. Eichert et al. 2008).

After these processes, different fractions of materials (ferrous metal, non-ferrous metals and plastics) are separated by mechanical and manual procedures (screen, drum magnet, eddy current separator). The shredding residues are often fed to energetic recovery where critical metals are distributed dissipatively and are lost for further recovery (Fröhlich 2009).

As analysed by Chancerel (2010) without a manual dismantling precious metals are often either sent to further mechanical pre-processing or sent to plastic recycling and lost: “It is assumed that in total, pre-processing through manual dismantling allows the recovery of 90% of the gold and palladium. The results have the same order of magnitude as the results of Meskers et al. (2009), who investigated only personal computers.”

5.2 Technologies for end-processing of WEEE

End-processing takes the dismantled components or output fractions produced in the pre-processing step and recovers metals and other materials, which can then be used as raw materials in the production of new products. The final recovery of critical metals from pre-

processed output fractions can take place at two different main types of facilities[24]: integrated smelters, copper smelters (cf. chapters 5.2.1-2). WEEE treatment solely by hydrometallurgical processes also exists but it has not been implemented on an industrial scale yet and is therefore neglected in the further assessment of material losses. Moreover, informal artisanal metal recycling ('backyard recycling'), common in developing countries, is not an issue in EU-27.

While WEEE collection takes place at a local to regional level and pre-processing at a regional to national level, end-processing of WEEE is a globalised service, with only few facilities in Europe. Umicore in Belgium recovers precious metals in an integrated smelter. Aurubis, Germany and Boliden, Sweden are copper smelters, which recover precious metals[25].

5.2.1 Integrated smelters

Integrated smelters, i.e. smelters combining pyrometallurgical and hydrometallurgical processes, recover precious metals, copper and other non-ferrous metals, including certain critical metals, while isolating hazardous substances. This process involves the integration of a copper smelter, a lead smelter (both pyrometallurgy) and hydrometallurgical metal recovery (leaching and electrowinning). Figure 6 shows a simplified diagram for an integrated smelter. Integrated smelters are able to recover the energy content of organic material and to recover several metals from personal computers and other WEEE groups to the same grade (quality) as primary producers. Precious and special metals (Pd, Au, Ag, Pt, Ru, Co, In, Te) are extracted with a collector metal (e.g. Cu) while other metals such as Li, Be, Ta, REE end up in the slag. Metals can be recovered from slag if thermodynamically feasible and economically viable, which depends on the metal price, concentration and the corresponding process costs (OECD 2010 a).
Integrated smelters are able to treat many kinds of WEEE (Hagelüken 2008):

- Printed circuit boards from computers, hard disk drives (HDD), mobile phones, TVs and monitors;
- Integrated circuits, capacitors, contacts;
- Output fractions from pre-processing with high content (after shredding and sorting);
- Other output fractions from mechanical processing with precious metal content;
- Li-Ion and NiMH batteries (in dedicated business lines);
- Entire devices smaller than 15 cm (e.g. mobile phones) with high precious metal content, after removal of the battery;
- Usually, the e-scrap is mixed for the initial smelting process with other precious metal containing materials such as catalysts, by-products from the non-ferrous industry (see next chapter 'Copper smelters') or primary ores.

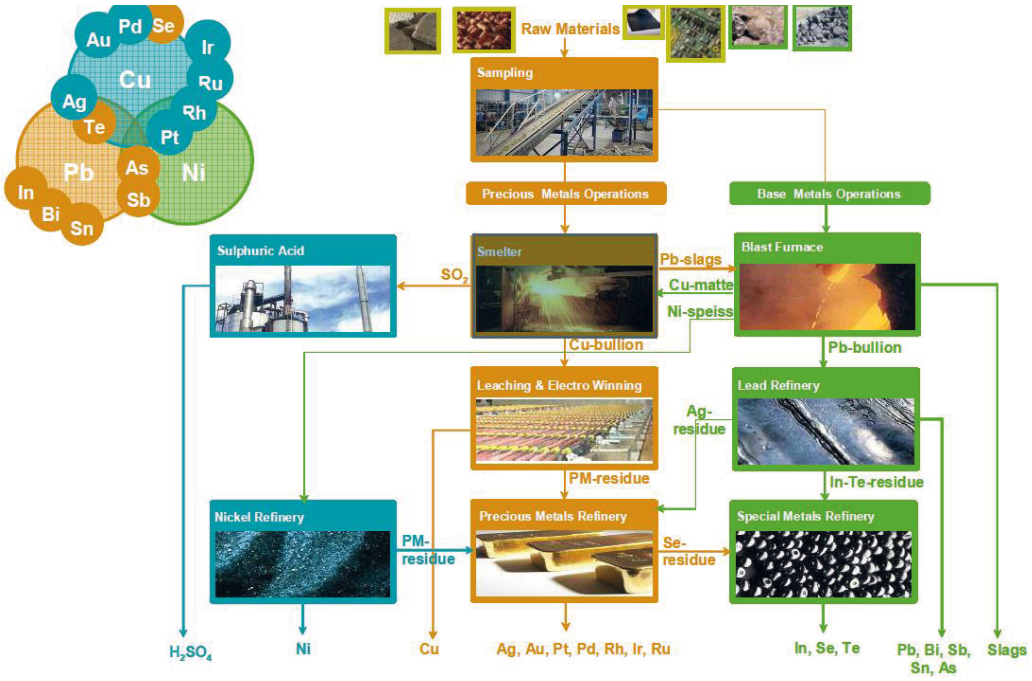
Integrated smelters need to have state-of-the-art off-gas treatment in place to deal with the emissions of toxic organic compounds (dioxins, furans) resulting from energy recovery from organic material (UNEP 2009, OECD 2010 a).

[24] The technical description of course does not cover the whole market, but focus on selected, representative plants.

[25] Facilities producing refractory metal products (W, Ta) are not suited to process end-of-life WEEE.

The economic driver for shipment of WEEE fractions to integrated smelter refineries are usually the contained precious metals (mainly gold, silver, palladium) and copper. However, state-of-the art operations have developed over time sophisticated flowsheets which enable the co-recovery of a number of base metals (lead, nickel, tin) and special metals (selenium, tellurium, antimony, arsenic, bismuth, partly indium). However, without the presence of the paying metals, the recovery of the other metals is usually not economically viable (Hagelüken & Corti, 2010).

Figure 6: Simplified flowsheet of Umicore's integrated smelter processes (UNEP 2009)



5.2.2 Copper smelters

As integrated smelters, copper smelters apply a combination of pyro- and hydrometallurgical processes to recover the main product copper cathodes. State-of-the-art copper smelters with appropriate off-gas-treatment are also able to treat material with organic content such as printed circuit boards or untreated small devices as mobile phones. Copper smelters use copper scrap, WEEE, and primary copper ore concentrate as input into the smelting process.

5.3 Losses of critical metals during pre-processing of WEEE

Losses occurring in pre-processing can be due to 1) the type and combination of processes used in pre-processing (cf. for example Gmünder 2007 and Willems et al. 2006), 2) the mismatch between the material streams produced in pre-processing and the amount and

type of metals that end-processing can recover[26] and 3) the limitations of the Laws of Chemistry and Physics. Furthermore the design of the product will affect the aforementioned factors.

For Germany Chancerel (2010) has analyzed the distribution of different small WEEE product groups to different ways of pre-processing and the resulting recovery rates for gold and palladium. As shown in Table 16 the most relevant procedure is 'Mech. 2' with a combination of manual and mechanical pre-processing which show significant potentials to improve the circular flows of critical metals even if main Printed Wire Boards are removed manually. The results for the recovery rates include the mechanical treatment of separated printed circuit boards, which is widely used after all kinds of pre-processing and especially after the manual removal of parts (cf. Fröhlich 2009, p. 562). The procedure 'no pre-processing' (No PP) only applies to mobile phones, because they can be end-processed entirely in appropriate facilities.

Table 16: Recovery rates for technologies used for gold and palladium achieved in 2007 by the pre-processing technologies used for formal treatment in Germany (Chancerel 2010)

	Distribution of WEEE over the process types (modified from Bolland 2009)			*Recovery rate of types of pre-processing*		*Total recovery rate of pre-processing*
Treatment type	No PP	Manual	Mech. 2	Manual	Mech. 2	
Mobile telephone	40 %	10 %	50 %	90 %	24 %	61 %
Desktop PC		24 %	76 %	90 %	50 %	60 %
CRT monitor		24 %	76 %	60 %	60 %	60 %
Large high-grade equipment		24 %	76 %	90 %	40 %	40 %
Small high-grade equipment		24 %	76 %	90 %	40 %	40 %

In general, the pre-processing of WEEE has to face the so called 'concentration dilemma': A reduction of the losses of precious metals possibly means reducing the concentration of precious metals in the fraction sent for precious metal recovery and increasing the losses of other materials like ferrous metals that cannot be recovered in processes for precious metals (cf. Chancerel 2010, p. 42).

When focusing on these critical metals, there is often a strong trade-off between the recycling rate and the economic viability of the process. However, for precious metals this trade-off only becomes apparent at much lower concentrations. This means that greater pre-processing effort - for example, by manual removal of medium and high grade circuit boards before shredding – can result in a net increase in profit because of the much higher precious metal yields (Hagelüken, C. (2012).

[26] Cf. Chancerel 2010 for a very detailed overview on the whole process and its losses of gold and palladium for mobile phones and screens.

Estimating raw material specific average EU-27 pre-processing efficiencies:

The pre-processing efficiency (recovery rate) is defined as the ratio of:

- The metal output (e.g. gold) at the pre-processing phase. Although pre-processed WEEE might be exported out of EU-27, a 'closed' system is assumed, which means that the entire output of pre-processing is end-processed in the EU (output of pre-processing = input to end-processing phase) and;
- The metal input (e.g. gold) to the pre-processing phase. Losses due to illegally exported WEEE out of the EU-27 and collected WEEE that end up on landfills are attributed to the collection phase. (Input to pre-processing phase = output of collection phase).

Since there are different pre-processing routes for WEEE which influences the loss of critical metals, it is necessary to construct an average EU-27 pre-processing route for each product group.

5.3.1 Mobile phones

Table 17: Relevant components and critical raw materials for mobile phones (ETC/SCP 2011)

Batteries (see 5.4.4)	Li, Co
Integrated circuits (microchips)	Co, In, Ag, Te, Be, Ga, Ge, Au, Pd
LCD (see 5.3.4)	In, W[27]
LED	In, Ta, Ga, Ge, REE
Printed Wire Boards	Ag, Au, Pd, Be

For mobile phones, four pre-processing routes are assumed:

1. No pre-processing: Only the batteries are removed. The batteries go to separate recycling systems and the entire device including the organic fractions (e.g. plastic) is sent to end-processing in integrated smelters. In this case, there are no losses of critical metals at the pre-processing phase.
2. Manual dismantling: Removal of PWB and other components containing critical metals.
3. Manual depollution followed by shredding and automated sorting (Mech 1).
4. Combination of manual and mechanical processing (Mech 2).

Recovery rates for gold and palladium and routes 'Manual' and 'Mech 2' are adopted from Table 16 (Chancerel 2010). Recovery rates for route Mech 1 are adopted from Chancerel 2009. It is assumed that all batteries are removed from the devices. Since batteries are the only component containing lithium, recovery rates for lithium are 100 % in all cases. It is further assumed that the amount of cobalt in the battery is much larger than in ICs. Therefore, the recovery rate for cobalt is also assumed to be 100 %. For routes with automated sorting (Mech 1 & Mech 2) recovery rates for precious metals are assumed to be equal to the recovery rates for gold while recovery rates for other metals are assumed to be negligible (0%). For manual dismantling, recovery rates for non-precious metals are assumed to

[27] Tungsten is relevant for LCDs in flat cable wiring, and also in other applications in metallic films to replace the traditional wiring solutions (copper or gold). However, it seems to be used in minor quantities only as a thin layer of sprayed powder.

be equal to precious metals. It is further assumed that the recovery rates for the different process routes are equal for all EU-27 countries.

The distribution of pre-processing routes is also adopted from Table 16, which implies the assumption that the distribution for EU-27 is equal to distribution in Germany. Since it can be assumed that WEEE processing in Germany is more advanced than EU-27 average, it is likely that EU-27 pre-processing efficiency is overestimated. The main cause for losses of critical metals from mobile phones after their collection is pre-processing together with other small WEEE appliances of the collection group according to the WEEE directive (EU-Commission, 2002). Table 18 shows the result of the estimation.

Table 18: Pre-processing efficiencies (metal recovery) for critical metals in mobile phones (red indicates assumption)

	No PP	Manual	Mech 1	Mech 2	Overall EU-27 recovery rate
EU-27 Distribution [Mass %]	40 %	10 %	0 %	50 %	
Metal Recovery Rates					
Ag	100 %	90 %	11 %	24 %	61 %
Co	100 %	100 %	100 %	100 %	100 %
In	100 %	90 %	0 %	0 %	49 %
Li	100 %	100 %	100 %	100 %	100 %
Ta	100 %	90 %	0 %	0 %	49 %
Te	100 %	90 %	0 %	0 %	49 %
W	100 %	90 %	0 %	0 %	49 %
Au	100 %	90 %	26 %	24 %	61 %
Be	100 %	90 %	0 %	0 %	49 %
Ga	100 %	90 %	0 %	0 %	49 %
Ge	100 %	90 %	0 %	0 %	49 %
Pd	100 %	90 %	26 %	24 %	61 %
Ru	100 %	90 %	26 %	24 %	61 %

5.3.2 Personal computers (desktop computers)

Table 18a: Relevant components and critical raw materials for desktop PCs (ETC/SCP 2011)

Integrated circuits (microchips)	Co, In, Ag, Te, W, Be, Ga, Ge, Au, Pd
LED	In, Ta, Ga, Ge, REE
Printed Wire Boards	Ag, Au, Pd, Be
Electric motor	Co
HDD	Ag, Ta, Be, Ru

Typical pre-processing process chains for personal computers (Chancerel/Bolland 2010):

1. A simple manual dismantling process (Manual 1), which represents a common routine procedure, is the removal of the motherboard, plugged-in Printed Wire Boards and contacts. Empirical studies indicate that the overall pre-processing efficiency of such a simple dismantling procedure for desktop computers is 80% for gold (silver: 49 %, palladium 66 %), which means that 80 % of the gold contained in the PCs entering the pre-processing phase reaches the end-processing phase while 25 % is lost due to material dissipation (Meskers 2009, Chancerel,/Boland, 2010).
2. The highest pre-processing efficiencies (97 % gold, 92 % silver, 99 % palladium) can be achieved by multi-level deep manual dismantling (Manual 2), which means that Printed Wire Boards contained in other components as HDD, ODD and PSU are further separated, which leads to a higher concentration of critical metals in the material for end-processing (Meskers 2009).
3. The worst case in terms of critical metals recovery is a manual depollution followed by shredding and automated sorting (Mech 1). (Gold 26 %, silver 11 %, palladium 26 %). (Chancerel 2009).
4. A combination of mechanical and manual processes (Mech 2) leads to gold recovery rates of 70 %. The components are separated by smashing, which is followed by handpicking of valuable components. Hazardous components are either removed manually before smashing (manual depollution) or afterwards by handpicking. The components are then reduced to small pieces by shredding or hammer milling and the output material is finally automatically sorted (Meskers 2009).

Assumptions are as described for mobile phones.

Table 19 shows the result of the estimation. Ruthenium can only be recovered by deep manual dismantling and manual sorting.

Table 19: Pre-processing efficiencies (metal recovery) for critical metals in desktop PCs (red indicates assumption)

	Manual 1	Manual 2	Mech 1	Mech 2	Overall EU-27 recovery rate
EU-27 Distribution [mass %]	24 %	0 %	0 %	76 %	
Metal recovery rates					
Ag	49 %	92 %	11 %	75 %	69 %
Co	80 %	97 %	0 %	0 %	19 %
In	80 %	97 %	0 %	0 %	19 %
Li	-	-	-	-	-
Ta	80 %	97 %	0 %	0 %	19 %
Te	80 %	97 %	0 %	0 %	19 %
W	80 %	97 %	0 %	0 %	19 %
Au	80 %	97 %	26 %	70 %	72 %
Be	80 %	97 %	0 %	0 %	19 %
Ga	80 %	97 %	0 %	0 %	19 %
Ge	80 %	97 %	0 %	0 %	19 %
Pd	66 %	99 %	26 %	41 %	47 %
Ru	0 %	97 %	26 %	70 %	53 %

5.3.3 Personal computers (notebooks and laptops)

Table 20: Relevant components and critical raw materials for notebook PCs (ETC/SCP 2011)

Batteries	Li, Co
Integrated circuits (microchips)	Co, In, Ag, Te, Be, Ga, Ge, Au, Pd
LCD	In, W
LED	In, Ta, Ga, Ge, REE
Printed Wire Boards	Ag, Au, Pd, Be
Electric motor ,	Co
HDD	Ag, Ta, Be, Ru

Apart from the removal of batteries and LCD display, dismantling and pre-processing processes for notebook computers are similar to the processes for desktop computers. It is assumed that all displays (LCD+LED backlight) and batteries are removed prior to further processing. Therefore, as described for mobile phones, recovery of lithium, cobalt and indium is assumed to be complete.

Table 21: Pre-processing efficiencies (metal recovery) for critical metals in notebook PCs (red indicates assumption)

	Manual 1	Manual 2	Mech 1	Mech 2	Overall EU-27 recovery rate
EU-27 Distribution [mass %]	24 %	0 %	0 %	76 %	
Metal recovery rates					
Ag	49 %	92 %	11 %	75 %	69 %
Co	100 %	100 %	100 %	100 %	100 %
In	100 %	100 %	100 %	100 %	100 %
Li	100 %	100 %	100 %	100 %	100 %
Ta	80 %	97 %	0 %	0 %	19 %
Te	80 %	97 %	0 %	0 %	19 %
W	80 %	97 %	0 %	0 %	19 %
Au	80 %	97 %	26 %	70 %	72 %
Be	80 %	97 %	0 %	0 %	19 %
Ga	80 %	97 %	0 %	0 %	19 %
Ge	80 %	97 %	0 %	0 %	19 %
Pd	66 %	99 %	26 %	41 %	47 %
Ru	0 %	97 %	26 %	70 %	53 %

5.3.4 TV and flat screen monitors

Table 22: Relevant components and critical raw materials for TVs and flat screen monitors (ETC/SCP 2011)

Integrated circuits (microchips)	Co, In, Ag, Te, Be, Ga, Ge, Au, Pd
LCD	In, W
LED	In, Ta, Ga, Ge, REE
Printed Wire Board	Ag, Au, Pd, Be
Plasma display	Ag
Resistor	Ge, Au, Pd, Ru
Wiring	W, Be, Au

Flat screen displays can be treated in three ways (Böni, H. and Widmer,R., 2011):

1. Manual dismantling.
2. Mechanical treatment (automatic).
3. Incineration in municipal incineration plants.

The recycling of indium contained in ITO and of IC from flat screen displays requires generally a thorough mechanical dismantling of the LCD panels (Böni, H. and Widmer,R., 2011). Flat screens mechanically treated or incinerated do not allow for any recovery of these target components.

Therefore, the manual dismantling of any flat screens follows generally a step-wise basic procedure (Böni, H. and Widmer,R., 2011):

1. cutting of cables,
2. removal of the socket,
3. opening the chassis,
4. disassembly of printed circuit board; fractionation of metals, plastics and LCD module,
5. fractionation of the LCD module (display unit) into LCD panel and background lighting (fluorescent tubes).

Specific LCD recycling procedures for the different product groups are described below:

Computer monitors
After dismantling the cables, the socket and the chassis (steps 1-3), the metal back panel and the printed wire boards normally can be easily dismounted. By doing so, fractions of plastic, ferrous metals and the printed wire boards can be separated for further treatment.
The display unit has to be opened very carefully to get access to the LCD backlight. Computer monitors normally contain between two and six fluorescent tubes that are plugged into rails which offer only low protection against damage, but from which they can be easily removed.

TV sets
Dismantling the cables, the socket and the chassis are rather the same as for computer monitors. However, the disassembly of the printed wire boards is more difficult if these are installed on the back panel of the device. Due to size and contrast requirements, TV sets often have more fluorescent tubes than computer monitors and they are placed behind the screen, In addition, the danger of destroying a tube is significantly higher because they are usually glued and additionally fixed.

Laptops

After separating the screen from the rest of the laptop, the display unit is removed from the plastic chassis (step 5). A special obstacle in this procedure is the application of very specific screw systems. The printed wire boards are usually plugged directly into the display units. Therefore, the boards are removed very carefully in order not to break any of the fluorescent tubes.

According to Chancerel 2010, about 25 % of monitors and screens in Germany undergo dismantling processes as described above, only in these cases can Indium be recovered (Manual).

In Germany about 75 % of the devices are treated with a combination of the manual removal of components containing hazardous or precious metals and shredding processes (Mech 2).

Although in both these cases (complete manual dismantling/ combination with shredding) the printed wire boards are removed, about 40 % of the contained precious metals are lost for further recovery (Chancerel 2010). For mobile phones it is assumed that non-precious metals are completely lost with automated sorting.

Table 23: Pre-processing efficiencies (metal recovery) for critical metals in TVs and flat screen monitors (red indicates assumption)

	No PP	Manual	Mech 2	Overall EU-27 recovery rate
EU-27 Distribution [mass %]	0 %	25 %	75 %	
Metal Recovery Rates				
Ag	0 %	60 %	60 %	60 %
Co	0 %	60 %	0 %	15 %
In	0 %	60 %	0 %	15 %
Li	0 %	60 %	0 %	15 %
Ta	0 %	60 %	0 %	15 %
Te	0 %	60 %	0 %	15 %
W	0 %	60 %	0 %	15 %
Au	0 %	60 %	60 %	60 %
Be	0 %	60 %	0 %	15 %
Ga	0 %	60 %	0 %	15 %
Ge	0 %	60 %	0 %	15 %
Pd	0 %	60 %	60 %	60 %
Ru	0 %	60 %	60 %	60 %

5.3.5 Solar energy modules (thin film and conventional)

There is currently only one industry-scale recycling plant for PV modules operating in Europe. It belongs to FirstSolar and recycles their CdTe-PV modules which were collected in Europe. Another pilot-scale recycling plant is operated by Sunicon in Freiberg, specialising in the recycling of crystalline PV modules. Dismantling of the EoL-modules for all types of modules involves the manual removal of junction boxes, cables and for crystalline PV

modules also the aluminium frame. What is left for the actual recycling process is the glass covered with the semi-conductor layers or the crystalline solar cells with the front glass and Tedlar® foil. For both types of PV modules (thin film and crystalline) the dismantled module also contains the EVA foil.

No losses of critical metals occur in the dismantling process since only external parts are removed from the system, which are then recycled via more appropriate processes. A factor that may lead in a loss of critical metals later in the process could be the incorrect handling of the modules during removal, collection and dismantling. Broken modules are said to be recyclable, with a lower efficiency, which cannot be quantified. In order to avoid such losses it is important to handle the collected modules with care during transport and dismantling.

5.3.6 Rechargeable batteries (as contained in WEEE)

Table 24: Relevant critical raw materials for batteries (ETC/SCP 2011)

Batteries	Li, Co, Ag

After removing the batteries from the WEEE, no further dismantling or even shredding takes place but they are either manually or automatically sorted. There are two main groups of rechargeable batteries used in EEE: NiMH and LiIon batteries. NiCd batteries are only allowed to be used in cordless power tools and the amount put on the market has been decreasing for some years. Therefore and because of the fact that no critical metals are used for NiCd-battery-production, only NiMH and LiIon batteries are taken into account for this report. During the recycling process both types of batteries are separated and sent for special treatment. In order to guarantee the optimum separation quality, special attention has to be paid to the collection, transportation and handling of the batteries before sorting.

It is necessary to send the batteries to be sorted in a condition where they are whole and non-sticky, so that they can be successfully recognised by the sorters or the machinery. If batteries stick together or are severely leaking then they are usually sent to the fraction along with the unsortable batteries which mainly end up in a special landfill or other non-specific treatment processes.

One of the problems often encountered is that different battery chemistries can look very similar at the sorting facility. If the batteries were poorly labelled during manufacture or if their markings have been destroyed during processing of the WEEE, they will, if manual sorting is used, end up in the unsorted ‘reject’ fraction. This will result in the loss of critical metals.

Automatic sorting does not rely on labelling. For example, the Swedish manufacturer Optisort produces an automatic sorting system designed to recognise the most common brands and types of batteries and so speeds up the sorting process. However, according to the firm it will always require the expertise of manual sorters whose experience enables them to recognise accurately the lesser known battery brands and chemistries. The system can automatically sort between 4 and 8 tonnes of waste portable batteries per day (0.5 to 1 tonne per hour) and can handle all types of portable batteries from D to button cells (button cells are separated but not sorted), including small cell phone batteries (Optisort, 2012).

No estimations about losses of critical metals due to inappropriate handling of batteries could be found in the literature.

5.4 Losses of critical metals during end-processing of WEEE

Estimating raw material specific average EU-27 end-processing efficiencies:

The end-processing efficiency (recovery rate) is defined as the ratio of:

- The metal output (e.g. gold) of the end-processing phase and;
- The metal input (e.g. gold) to the end-processing phase. Although pre-processed WEEE is traded globally, a 'closed' model is assumed, which means that export of pre-processed WEEE out of the EU-27 and import of pre-processed WEEE is neglected. (Input to end-processing phase = output of pre-processing phase).

5.4.1 Mobile phones, desktop computers, notebooks and laptops

After pre-processing, scrap from components (e.g. PRINTED WIRE BOARDs) from mobile phones, desktop computers as well as laptops are commonly treated as a mixture in the phase of end-processing (see 5.2.1). For this reason no product group-specific specific losses can be calculated but only the recovery efficiency for different metals can be taken into account.

Table 25 compares recovery rates for selected critical metals for integrated smelters and copper smelters. Unlike integrated smelters, copper smelters only recover some precious metals as gold and silver. However, this does not necessarily mean that other critical metals contained in processed e-scrap are lost for recovery, because copper smelters sell metal containing by-products (drosses, mattes, speiss, anode slimes) to facilities capable of further recovering remaining metals (Cui 2008). Because of the indirect process route, the recovery rate for metals taking this route is assumed to be a little lower than for metals processed directly in integrated smelters (Hagelüken 2011).

Table 25 gives an overview of end-processing efficiencies for the entire recovery phase. Figures in parentheses indicate metals contained in by-products processed in integrated smelters. Unlike the estimations for losses during the pre-processing phase, it is not necessary to construct an average EU-27 end-processing route, because it can be expected that the share of e-scrap treated in integrated smelters and copper smelters only has a minor influence on overall recovery rates. Therefore, the figures in the first column are used for further assessment.

Table 25: Recovery rate for metals in different high efficient pyrometallurgical operations (Hagelüken 2009, Hagelüken 2011, Lehner 2011)

	Integrated smelter	Copper smelter:
Ag	> 95 %	95 %
Co	90 %	(90 %)
In	< 50 %, partly to slag	0 % residue
Li	0 % slag	0 % slag
Ta	0 % slag	0 % slag
Te	> 90 % recovered from Cu-alloy	80 %/ (90 % as Copper-Telluride)
W	0 % slag	0 % slag
Au	> 95 %	95 %
Be	0 % , lost in Cu-alloy or slag	0 % , lost in Cu-alloy or slag
Ga	0 % fly ash/slag	0 % fly ash/slag
Ge	0 % fly ash/slag	0 % fly ash/residue
Pd	> 95 %	95 % / (90 % as concentrate)
Ru	95 % (selective pre-processing assumed)	90 % / (90 % as concentrate)

* Based on Umicore (Hoboken, Belgium, ** Based on Boliden, Rönnskar (Skellefteham, Sweden) or Aurubis, (Hamburg/Lünen, Germany)

For thermodynamic and economic reasons, it is very unlikely that the refractory metals tungsten and tantalum, as well as gallium or germanium will be recovered from WEEE (Hagelüken 2011).

End-processing for batteries and flat screen monitors and related recovery rates (In, Co, Li) are described below (5.4.2, 5.4.4).

5.4.2 TV and flat screen monitors

As previously described, some parts of dismantled TV sets and flat screen monitors can be supplied to specific recycling facilities for the recovery of indium. Recycling of liquid crystal displays does to a large degree focus on the recycling of indium tin oxide (ITO), the functional material used commonly in today's flat screen displays, i.e. LCD, plasma displays, and OLED displays.

On the global scale, recovery of indium from post-consumer goods is still not widely-used[28], [29] as highly-developed and specialised technical processes are required. Several

[28] For indium, recovery from new scrap (about 1 000 tons of Indium) clearly exceeds recovery from old scraps (Jorgenson and George 2005), while also the indium concentrations are higher and the scraps are purer. In Europe, recycling processes were developed in 2010 on an industrial scale for so-called *sputtering targets* (Meskers et al. 2010, Hagelüken and Meskers 2010). The recycling of ITO is predominantly located in Japan, China and South Korea, where LCD production is predominantly located.

[29] The Umicore plant at Hoboken/Antwerp – one of the world largest sites for the recycling of precious metals in the world – has current capacities to produce 50 tons (mainly from primary sources, including production from new scraps). Umicorre recovering indium mainly from (zinc) smelter by products and to a small extent from WEEE streams. Moreover, dedicated Umicore processes exist

LCD manufacturers are reported to recycle ITO from LCD displays (Rüth 2010). For example, Sharp, a leading global LCD producer, has developed a rather simple energy- and cost-efficient hydrometallurgical process to recycle highly-pure indium from scrap LCD panels that uses non-problematic chemicals (JCN 2005); however, the recycling volumes have not been published (Rüth 2010).

Indium tin oxide (ITO) is carried on glass substrates when entering the recovery plants (Hagelüken and Meskers 2009). The processing steps are (Tolcin 2009):

1. Crushing of LCD panels into millimetre-sized particles;
2. Dissolving the ITO by immersion in acid solution: ITO can be leached acidly (total dissolution);
3. Recovery of the indium from the solution (metals dissolved, which are more electropositive than indium, have to be precipitated firstly).

Today, recycling of LCD is partly established in Japan. In Europe, recovery of postconsumer goods containing indium has not been reported yet, as adjusted technical procedures are still missing (Böni, H. and Widmer, R. 2011).

For the recycling processes described above, no numbers (so far) are available regarding losses. Where a specific recovery facility for indium/ITO is not available and the display screens are, for example, transferred to waste incineration plants, the indium content is fully lost or transferred to metals where indium acts as an unintended alloy metal.

Due to the average lifetime in excess of 5 years for flat panel displays and their relatively recent market penetration, the amount of indium containing post-consumer products that reach the recycling facilities is still rather low, and so are the indium losses from LCD displays. However, the volumes are rising continuously.

5.4.3 Solar energy modules (thin film and conventional)

In order to be able to better understand what material flows can be expected from PV module recycling, Table 40 in Annex IV gives an overview about the average composition of a PV module (crystalline and thinfilm).

The content of critical metals in PV modules is very low which makes it usually rather difficult to recover them efficiently. Also, the rare metals usually occur in compounds such as CdTe or CuInGaSe which have to be dissolved during wet-chemical processes in order to recover the single fractions of the rare metals. To ensure the best possible recovery it is also necessary to separate the different PV module types (crystalline, CdTe, a-Si, CIS/CIGS).

Crystalline PV modules must be treated using a combination of thermal and wet-chemical processes. First the modules are usually crushed and then thermally treated to remove the plastic parts (EVA foil and Tedlar). Afterwards, the remaining wafers are treated chemically to remove mainly silver.

The CdTe modules from First Solar are treated in a hydro-mechanical process. Firstly they are crushed into pieces of about 5mm which is considered to be the optimal size for achieving the best recovery rates. The thinfilm layers are then removed using an acidic solution. The dissolved and solid parts have to be separated through an archimedic screw. The solid parts are further separated in a vibration filter so that a glass and an EVA fraction can be

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for recycling of ITO targets (new scraps). Via an R&D project the company is currently exploring with partners a recycling process to recycle LCD.

derived. In order to be able to recycle the glass (mainly in the mineral wool sector) it has to be further cleaned in a 3-staged counter flow system. The waste water contains low concentrations of metals which are recovered in the waste water treatment system together with the liquid part from thinfilm removal step. In this system the dissolved metals are chemically precipitated in solutions with decreasing pH. In a thickener, solid parts are separated from the clear water which is removed. In a chamber filter press more water is removed so that the dried filter cake can be sent for further treatment to an external company. There, they recover Cd and Te from the filter cake to produce CdTe for use in CdTe module production. More than 90 % of the glass fraction can be recovered and 95 % of the semiconductor metals.

Important steps where metals can get lost are the crushing (either too big or small) and the wet-chemical recovery process. As for the crushing, optimization of the hammer mill should be considered and for the wet-chemical process optimized pH-values in the solutions should be aimed at. Unfortunately, there is no specific information about the influence of the pH or particle size on the recovery rates.

5.4.4 Rechargeable batteries (as contained in WEEE)

NiMH batteries are normally treated in a vacuum-thermal process due to their high reactivity which results from the hydrogen in the battery. Plastics are separated from the metals and a high-value nickel-containing product is the main result from this recovery process. Only some of the NiMH batteries contain cobalt in very low amounts. It is technically difficult and not financially feasible to recover such low amounts.

For portable electronic devices high-quality treatment facilities exist which treat NiMH and LiIon batteries together in the same metallurgical process, a separation into the two different types is not required. The big advantage of the process is that it is very flexible with regard to varying battery types, their different chemistries and cobalt contents[30].

As for LiIon batteries, much research is currently being conducted since large amounts of used batteries are expected in a few years' time – especially from electric vehicles but also from laptops and other electric devices. Currently, LiIon batteries can be treated via metallurgical processes (e.g. at Umicore) where cobalt, nickel and copper are recovered. Recovery rates for cobalt from LiIon and NiMH batteries are assumed to be 90 % (Hagelüken 2011). Lithium is used as reducing agent only and is not recovered.[31] The recovery of lithium is technically feasible but plants exist only in pilot scale. Hence, there is a high potential for increasing the recycling efficiencies of lithium in batteries.

[30] For further details see http://www.batteryrecycling.umicore.com/UBR/.

[31] However, the lithium containing slag can be sold as special additive to concrete where it provides concrete cancer. For some of these applications otherwise lithium would have to be added, so in these cases the lithium can be utilised without the necessity to refine the metal itself.

6 The recovered and potential recycling amounts of critical metals in WEEE

The aim of this chapter is to estimate the overall efficiency of the recycling chain. For each of the product groups and each of the critical metals addressed in the report, the final recovery rates and the absolute amounts of critical metals recovered are calculated by multiplying the quantity of each metal per kg of product with the results for collection rates and with metal recovery rates in pre- and end-processing.

As the figures for the collection rates differ widely over time, results are presented for the year 2008 (and 2009 for batteries) assuming stable efficiencies for pre- and end-processing. The rates are also used for the calculations for 2010 and 2015.

6.1 Mobile phones

MOE & METI (2010) provides information on the material composition of mobile phones (without batteries) based on Japanese products, including the critical metal content. Due to absence of European figures, these composition figures are used to estimate the recovery of critical metals through the different waste management stages. The Japanese data contain composition analysis of 15 different models of mobile phones. The average composition of two representative models (one with camera and one without), collected as waste in 2010, was used.

The estimated overall efficiency for recovery of critical metals from waste mobile phones is for all metals included. None of the metals included in this report are recovered at a rate of more than 3 % of content in the waste stream. This is mainly due to the low collection rate of used mobile phones calculated in chapter 4: even if the pre- and end-processing stages were able to deliver 100 % efficiency, recovery amount would be capped by the 3 % collection rate. This extremely low collection figure is caused by a high share of waste products either not entering the waste management system (horded in households or sold beyond the EU) or entering the waste management system as mixed municipal waste (i.e. not as WEEE).

Table 26 shows the total recovered quantities of the critical metals, based on the calculated recovery rates and the waste arisings calculated in chapter 4. The total available critical metals in weight are shown in order to demonstrate the potential recovery in an ideal 100 % efficient system. The calculations are based on the 2008 total efficiency as shown in Table 26.

Table 26: Estimated efficiency of the recycling chain for mobile phones in 2008 stated in % and the recovery and available critical metals in mobile phones in the EU for selected years stated in kg

						2008		2010		2015	
Metals	g of metal/kg of product	Collection	Pre-Processing	End-Processing	Final*	Mobile phone waste in tonnes		Mobile phone waste in tonnes		Mobile phone waste in tonnes	
						34 289		36 621		31 523	
		Recovery (%)	Recovery (%)	Recovery (%)	Recovery (%)	Recovered in kg	Available in kg	Recovered in kg	Available in kg	Recovered in kg	Available in kg
Ag	0.9975	3%	61%	95%	2%	595	34 203	635	36 530	547	31 445
Co	0.177	3%	100%	90%	3%	164	6 069	175	6 482	151	5 580
In	0.045	3%	49%	0%	0%	0	1 543	0	1 648	0	1 419
Li	0.0045	3%	100%	0%	0%	0	154	0	165	0	142
Ta	0.028	3%	49%	0%	0%	0	960	0	1 025	0	883
Te	0.0505	3%	49%	90%	2%	23	1 732	24	1 849	21	1 592
W	1.4685	3%	49%	0%	0%	0	50 354	0	53 778	0	46 292
Au	0.389	3%	61%	95%	2%	232	13 338	248	14 246	213	12 263
Be	0.011	3%	49%	0%	0%	0	377	0	403	0	347
Ga	0.0275	3%	49%	0%	0%	0	943	0	1 007	0	867
Ge	0.0215	3%	49%	0%	0%	0	737	0	787	0	678
Pd	0.0595	3%	61%	95%	2%	35	2 040	38	2 179	33	1 876
Ru	-	3%	49%	0%	0%	-	-	-	-	-	-

Source: MOE & METI , 2010; Table 12; Table 14 and Table 18
* Rounded final percentage recover rate resulting from multiplying collection, pre- and end-processing efficiencies.

6.2 Personal computers (desktop computers)

Shingkikai (2011) contains information on the material composition of desktop computers without the monitors based on sampling in Japanese waste management for small electronics. It is possible to estimate the recovery in weight of critical metals for desktop computers in Europe by combining the information in this study with the losses estimated in chapters 4 and 5.

In Table 27 the analysis of the overall recycling efficiency for desktops shows that the critical metals contained can be divided into two groups: the ones that are not targeted at all by the end-processing operations and, thus have a 0 % efficiency; and the metals that are recovered in all phases which are recovered by 20-40 % overall. Again the greatest losses occur in the collection phase.

The second part of the table shows the recovered and available critical metals in European waste desktop PCs in 2008, 2010 and 2015, based on the arising of waste as calculated in chapter 4. Table 27 shows the overall recovered quantities regardless of the step where they occur. The resources available in discarded desktop PCs are considerable and the potential for an increase is high for most metals.

Table 27: Estimated efficiency of the recycling chain for desktop PCs in 2008 stated in % and the recovery and available critical metals in desktop PCs in the EU for selected years stated in kg

						2008		2010		2015	
Metals	g of metal/kg of product	Collection	Pre-Processing	End-Processing	Final*	Desktop computers waste in tonnes		Desktop computers waste in tonnes		Desktop computers waste in tonnes	
						89,166		93,587		95,973	
		Recovery (%)	Recovery (%)	Recovery (%)	Recovery (%)	Recovered in kg	Available in kg	Recovered in kg	Available in kg	Recovered in kg	Available in kg
Ag	0.3761	55%	69%	95%	36%	12,089	33,531	12,688	35,194	13,012	36,091
Co	0.0171	55%	19%	90%	9%	143	1,522	150	1,597	154	1,638
In	0.0000	55%	19%	0%	0%	0	0	0	0	0	0
Li	0.0000	55%	0%	0%	0%	0	0	0	0	0	0
Ta	0.0726	55%	19%	0%	0%	0	6,477	0	6,798	0	6,971
Te	0.0002	55%	19%	90%	9%	2	18	2	19	2	19
W	0.0199	55%	19%	0%	0%	0	1,773	0	1,861	0	1,908
Au	0.0610	55%	72%	95%	38%	2,045	5,436	2,147	5,706	2,201	5,851
Be	0.0002	55%	19%	0%	0%	0	18	0	19	0	19
Ga	0.0026	55%	19%	0%	0%	0	234	0	246	0	252
Ge	0.0000	55%	19%	0%	0%	0	0	0	0	0	0
Pd	0.0308	55%	47%	95%	25%	675	2,749	708	2,885	727	2,958
Ru	0.0012	55%	53%	95%	28%	30	109	32	114	33	117

Source: Shingkikai ,2011; Table 12; Table 14 and Table 19
* Rounded final percentage recover rate resulting from multiplying collection, pre- and end-processing efficiencies.

6.3 Personal computers (notebooks and laptops)

Shingkikai (2011) contains information on the critical metal content of laptops (without batteries), but does not include data on the indium contained in laptop LCD-displays. Therefore, data for indium in notebooks has been taken from Buchert et. al. (2012). This information, together with the waste amounts calculated in chapter 4 and the losses estimated in chapters 4 and 5, makes it possible to estimate the recovery of critical metals in Europe from waste laptops and the overall efficiency of the laptops waste management system.

Laptops and notebooks present a picture similar to desktops. The metals which are targeted by the end-processing phase are recovered at an overall rate of around 10-20 %, significantly lower than desktops. Again, the collection efficiency is responsible for the lower values compared to desktops.

Based on the time series for waste arising from laptops in the EU, calculated in chapter 4, it is possible to estimate the total recovered and total available quantities of critical metals in this waste stream. Table 28 below contains the results of this calculation for selected years, taking into account the overall recovery efficiency of 2008.

Table 28: Estimated efficiency of the recycling chain for laptop PCs in 2008 stated in % and the recovered and available critical metals in laptop PCs in the EU for selected years stated in kg

						2008		2010		2015	
Metals	g of metal/kg of product	Collection	Pre-Processing	End-Processing	Final*	Laptops waste in tonnes		Laptops computers waste in tonnes		Laptops computers waste in tonnes	
						34,518		53,549		126,775	
		Recovery (%)	Recovery (%)	Recovery (%)	Recovery (%)	Recovered in kg	Available in kg	Recovered in kg	Available in kg	Recovered in kg	Available in kg
Ag	0.3990	25%	69%	95%	16%	2,257	13,773	3,502	21,367	8,290	50,586
Co	0.0191	25%	100%	90%	23%	148	658	230	1,021	544	2,417
In	0.0200	25%	100%	0%	0%	0	690	0	1,071	0	2,536
Li	0.0000	25%	100%	0%	0%	0	0	0	0	0	0
Ta	0.8472	25%	19%	0%	0%	0	29,243	0	45,366	0	107,402
Te	0.0000	25%	19%	90%	4%	0	0	0	0	0	0
W	0.0186	25%	19%	0%	0%	0	643	0	997	0	2,361
Au	0.1426	25%	72%	95%	17%	841	4,921	1,305	7,634	3,090	18,073
Be	0.0074	25%	19%	0%	0%	0	255	0	396	0	937
Ga	0.0018	25%	19%	0%	0%	0	61	0	94	0	222
Ge	0.0000	25%	19%	0%	0%	0	0	0	0	0	0
Pd	0.0568	25%	47%	95%	11%	219	1,962	340	3,043	804	7,204
Ru	0.0028	25%	53%	95%	13%	12	95	19	148	44	351

Source: Shingkikai ,2011; Table 12; Table 14 and Table 21
* Rounded final percentage recover rate resulting from multiplying collection, pre- and end-processing efficiencies.

6.4 TV and flat screen monitors

Shingkikai (2011) investigates the material composition of desktop monitors. Based on the assumption that a large proportion of flat screens match the technology used for desktop computer monitors, and in the absence of other data sources, this composition is used in this report for all flat screens. However, data for the indium content of flat screen monitors has been taken from Buchert et. al (2012). Combining this composition and the losses of critical metals, as calculated in previous chapters, it is possible to estimate the recovery per kg of product of the selected critical metals.

Combining this information with the waste arisings calculated in chapter 4 allows the estimation of the total recovered and available quantities of critical metals in flat screens waste in Europe. Table 29 show the actual and potential recovery of the metals contained in flat screens.

In flat screens, the end-processing phase targets only some metals, but with a high efficiency. Again, the very low collection rates largely explain the low overall metal recovery rate of 12-13 %.

Table 29: Estimated efficiency of the recycling chain TVs and flat screen monitors in 2008 stated in % and the recovery and available critical metals in TVs and flat screen monitors in the EU for selected years stated in kg

						2008		2010		2015	
Metals	g of metal/kg of product	Collection	Pre-Processing	End-Processing	Final*	Flatscreens waste in tonnes		Flatscreens waste in tonnes		Flatscreens waste in tonnes	
						76,197		129,409		346,363	
		Recovery (%)	Recovery (%)	Recovery (%)	Recovery (%)	Recovered in kg	Available in kg	Recovered in kg	Available in kg	Recovered in kg	Available in kg
Ag	0.0326	23%	60%	95%	13%	325	2,482	553	4,215	1,479	11,282
Co	0.0012	23%	15%	90%	3%	3	94	5	159	13	426
In	0.0150	23%	15%	0%	0%	0	1,143	0	1,941	0	5,195
Li	0.0012	23%	15%	0%	0%	0	94	0	159	0	426
Ta	0.0000	23%	15%	0%	0%	0	0	0	0	0	0
Te	0.0000	23%	15%	90%	3%	0	0	0	0	0	0
W	0.0000	23%	15%	0%	0%	0	0	0	0	0	0
Au	0.0055	23%	60%	95%	13%	55	421	94	716	251	1,916
Be	0.0000	23%	15%	0%	0%	0	0	0	0	0	0
Ga	0.0000	23%	15%	0%	0%	0	0	0	0	0	0
Ge	0.0000	23%	15%	0%	0%	0	0	0	0	0	0
Pd	0.0006	23%	60%	95%	13%	6	47	10	80	28	213
Ru	0.0000	23%	60%	95%	13%	0	0	0	0	0	0

Source: Shingkikai ,2011; Table 12; Table 14 and Table 23
* Rounded final percentage recover rate resulting from multiplying collection, pre- and end-processing efficiencies.

The estimate for 2010 seems reasonable compared with collection figures of discarded LCD TVs and flat screen monitors for Denmark. Based on a survey, it is estimated that about 2 500 tonnes of TVs and flat screen monitors were collected in Denmark in 2011 (Jacobsen, H., 2012). In 2010 the Danish GDP was approximately 1.90 % of EU's total GDP (Eurostat, 2012). If the Danish collection is up-scaled based on GDP it gives an EU collected amount of 131 578 tonnes for 2011. The GDP growth in the EU from 2010 to 2011was only on 0.6 % and therefore it seems that the projection in Table 29 has a reasonable quality.

6.5 Solar energy modules (thin film and conventional)

Since solar module recycling is still developing, with only one industrial-scale facility in EU-27, only a possible to make a rough estimate. Based on information from an Ökopol study, an average maximum recovery rate of recovery for metals of 30% can be assumed for 2015 (Ökopol, 2010). However, we have not included solar energy modules in the total calculations.

6.6 Rechargeable batteries (as contained in WEEE)

Oguchi and Masahiro (2007) have estimated a composition for both types of rechargeable batteries relevant to this report - NiMH and Li-Ion. Based on a study by USGS (2009) it is possible to differentiate between the amount of cobalt and lithium for batteries used in laptops and those in mobile phones.

By using these material compositions, the waste arisings from chapter 4 and the assumptions made in chapter 5, it is possible to calculate the recovery of cobalt and lithium, through all waste management processes. Based on German collection data from 2009 (UBA, 2011) it is assumed that 55 % of collected batteries are of the NiMH type and 45 % are Li-Ion.

In the case of rechargeable batteries, the last step in the recovery process for rechargeable batteries – end-processing (smelting) – does not recover lithium, which means that all lithium contained in the batteries is lost in the final step. Similar to other products examined here, the collection rate for batteries is also low, but in this case smelting is also a critical step for losses.

The total recovered and available quantities of lithium and cobalt in waste rechargeable batteries can be estimated by applying the efficiencies to the waste arisings as estimated in chapter 4. Table 30 and Table 31 below show the results of these calculations.

Table 30: Estimated efficiency of the recycling chain for mobile phone batteries in 2008 stated in % and the recovery and available critical metals in mobile phone batteries in the EU for selected years stated in kg

							2008		2010		2015	
	Metals	g of metal/kg of product	Collection	Pre-Processing	End-Processing	Final*	Mobile phone batteries waste in tonnes		Mobile phone batteries waste in tonnes		Mobile phone batteries waste in tonnes	
							12 689		13 552		11 666	
			Recovery (%)	Recovery (%)	Recovery (%)	Recovery (%)	Recovered in kg	Available in kg	Recovered in kg	Available in kg	Recovered in kg	Available in kg
NiMH	Co	36	14%	100%	0%	0%	0	251 242	0	268 330	0	230 987
	Li	0.95	14%	100%	0%	0%	0	6 630	0	7 081	0	6 095
Li-Ion	Co	174	14%	100%	90%	13%	125 187	993 549	133 701	1 061 122	115 094	913 448
	Li	17	14%	100%	0%	0%	0	97 071	0	103 673	0	89 245

* Rounded final percentage recover rate resulting from multiplying collection, pre- and end-processing efficiencies.

Table 31: Estimated efficiency of the recycling chain for laptop batteries in 2008 stated in % and the recovery and available critical metals in laptop batteries in the EU for selected years stated in kg

							2008		2010		2015	
	Metals	g of metal/kg of product	Collection	Pre-Processing	End-Processing	Final*	Laptop batteries waste in tonnes		Laptop batteries waste in tonnes		Laptop batteries waste in tonnes	
							7 147		11 087		26 247	
			Recovery (%)	Recovery (%)	Recovery (%)	Recovery (%)	Recovered in kg	Available in kg	Recovered in kg	Available in kg	Recovered in kg	Available in kg
NiMH	Co	1.25	14%	100%	0%	0%	0	4 914	0	7 622	0	18 045
	Li	0	14%	100%	0%	0%	0	0	0	0	0	0
Li-Ion	Co	115	14%	100%	90%	13%	46 602	369 857	72 293	573 752	171 144	1 358 282
	Li	1.3	14%	100%	0%	0%	0	4 181	0	6 486	0	15 354

* Rounded final percentage recover rate resulting from multiplying collection, pre- and end-processing efficiencies.

6.7 All products

Based on the analysis performed in chapter 6, it is possible to assess the recovery and availability of critical metals in the selected electronic products' waste. By adding all recovered and available quantities, a total availability and recover of these metals from these products can be calculated from 2008 until 2015. However, one must also bear in mind that these

calculations are subject to all of the assumptions underlined in previous chapters. Table 32 summarises this calculation.

Table 32: Recovered and available quantities of critical metals from the waste of mobile phones, desktop and laptop computers, flat screens and re-chargeable batteries (Contained in WEEE), EU-27

Totals (exc.PV modules)		2008		2010		2015	
		254,006,000		337,805,000		638,547,000	
		Recovered (kg)	Available (kg)	Recovered (kg)	Available (kg)	Recovered (kg)	Available (kg)
	Ag	15,266	83,990	17,377	97,306	23,327	129,404
	Co	125,645	1,253,134	134,261	1,338,710	115,956	1,154,495
	In	0	3,376	0	4,660	0	9,150
	Li	0	103,949	0	111,078	0	95,908
	Ta	0	36,680	0	53,189	0	115,255
	Te	25	1,749	26	1,868	23	1,611
	W	0	52,769	0	56,636	0	50,561
	Au	3,174	24,117	3,793	28,301	5,756	38,103
	Be	0	650	0	817	0	1,303
	Ga	0	1,238	0	1,347	0	1,341
	Ge	0	737	0	787	0	678
	Pd	936	6,797	1,096	8,186	1,591	12,251
	Ru	42	205	50	263	77	468
	total	145,087	1,569,391	156,605	1,703,149	146,730	1,610,527

6.8 Demand and supply of metals

The European Commissions (2010)[32] provide estimations for the global demand for the selected metals for the EEE sector. Table 33 shows how much of this global demand can be covered by recycling the five selected product groups in Europe (no data are available for the total European demand for the EEE sector). Except for tellurium and palladium all coverage rates are below 10 %, some are surprisingly low such as indium, with less than 1%.

These results highlight the uncertainties in the assumptions of our model regarding metal contents, collection rates and the efficiency of the recycling chain etc., but can also be explained by some characteristics of the EEE sector.

The dynamic growth of the sector means that even a 100 % recycling rate would not be sufficient to cover the increasing demand for the metals. Especially for new products like flat screens, there may be a considerable delay between the products being placed on the market and them becoming waste and being available for recycling. However, the large increase in sales of flat panel displays over the past few years will result in a big increase in end-of-life products in the coming years e.g. for indium, the available amount in waste

[32] Reference to global production and consumption of metals can be found in Annex V of the report.

products in 2015 will be about three times higher than today. On the other hand, new products will enter the market and again will be available for recycling only with a certain time gap.

Table 33: The potential available amount of recycled critical metals in the selected product groups in 2008 and 2015 related to the total global amount needed for the production of EEE. Amounts stated in tonnes and percentage

Metals	recovered from waste (mobile phones, laptops, PCs, flat screens and batteries)	available in waste (mobile phones, laptops, PCs, flat screens and batteries)	Global demand 2008	Global EEE demand 2008	Coverage of Global EEE demand 2008 (with recovery of all available metals)	Coverage of Global EEE demand 2015 (with recovery of all available metals)
Ag	15.27	83.99	21 300	5 100	1.65%	2.54%
Co	125.65	1 253.13	75 900	20 500	6.11%	5.63%
In	0.00	3.38	568	420	0.80%	2.18%
Li	0.00	103.95	17 700	3 540	2.94%	2.71%
Ta	0.00	36.68	1 160	696	5.27%	16.56%
Te	0.02	1.75	135 in 2007 (Wittmer et al 2011)	15	11.66%	10.74%
W	0.00	52.77	55 950	5 950	0.89%	0.85%
Au	3.17	24.12	1450 in 2009 (USGS)	294	8.20%	12.96%
Be	0.00	0.65	141	56	1.16%	2.33%
Ga	0.00	1.24	78	51	2.43%	2.63%
Ge	0.00	0.74	139	21	3.51%	3.23%
Pd	0.94	6.80	220 in 2009 (Johnson Matthey, 2009)	42	16.18%	29.17%
Ru	0.04	0.20	18 in 2009 (Johnson Matthey, 2009)	10	2.05%	4.68%

Obtaining the changing shares of specific products in the WEEE stream is one of the most significant data obstacles: only the weights of aggregated collection groups are reported. As shown for Germany in Table 34, the share of mobile phones in total WEEE collection has quadrupled in the last five years. Such data is not available for all products and not for all European countries. Using the composition of the WEEE collection in 2007 thus might lead to a relevant underestimation of the amount of metals available in WEEE.

Table 34: Share of mobile phones in WEEE collection in Germany, based on statistical analysis by EAR

Mobile phones	2006	2007	2008	2009	2010	2011	2012
Weight based share of collection groups 3+4, in %	0.1	0.1	0.1	0.41	0.25	0.22	0.45

Source: http://www.stiftung- ear.de/service_und_aktuelles/kennzahlen/zusammensetzung_gemischter_sammelgruppen

Table 35 shows the size of the European and Global markets for four of the selected products. Although the European market is significant, for some types of product – desktop PCs for example – it accounts for only a small share of the global market. This limits the proportion of demand for critical metals that can be covered by recycling EU products.

Table 35: EU market share for selected products 2009, in units

	Number of units put the EU market, 2009	Number of units put on the GLOBAL market, 2009	European market share, 2009
Mobile phones	255 957 005	1 211 239 600	21.1%
Desktop PCs	8 849 550	136 200 000	6.5%
Laptop PCs and palm-top organisers	53 323 323	168 700 000	31.6%
Flat screens	40 839 883	320 000 000	12.8%

Sources:
EU sales figures:
Mobile phones, desktop PCs and laptops: Eurostat PRODCOM Database (2011)
Flatscreen: own calculations based on DE, PT and DK sampling.
Global sales figures:
Mobile phones: Gartner, 2011
Desktop and laptop PCs: ICD, 2010
Flatscreens: combined flatscreen TV sales and flatscreen monitors: Broadcastengineering, 2012 and Financial Times, 2012

Table 36 and 37 show the demand for silver and indium for the five products sold in the EU and globally, together with the total global demand for these metals for EEE and in all applications. European demand for silver and indium is estimated based on the metal contents figures for the five products and the numbers of products put on the market in Europe. Using the European share of the global market for these products, the European demand is extrapolated to the global level and compared to the global demand of the EEE sector as calculated in the study by European Commission (2010). The global sales of the four products contain about 1050 tonnes of silver (~21 % of the 5 100 tonnes global demand for silver for EEE) and about 60 tonnes of indium (~15 % of the global demand for indium for EEE).

Even with full recovery, the wastes of the selected five products in 2009 only contain sufficient metals to cover a limited share of the overall demand for metals within the European EEE sector in 2010. The **silver** contained in the waste of the five products generated in 2009 could fulfil approximately 60% of the demand for silver for the same five products sold in 2010, or 11% of total demand for silver for EEE equipment sold in Europe in 2010. The **indium** contained in the waste of the five products generated in 2009 could fulfil approximately 35 % of the demand for indium for the same five products sold in 2010 or 5 % of the demand for indium for all EEE equipment sold in Europe in 2010. This is not a surprise given the increasing year-on-year sales of these products.

Table 36: Relevance of the selected products for the global demand for silver, 2010

	European market share, 2009	EU demand(a) in 2009 for Silver for respective products (tonnes)	Global demand(a) in 2009 for Silver for respective products (tonnes)	Global demand for Silver for all EEE products (EC 2010) (tonnes)	Total Global demand for Silver (EC 2010) (tonnes)
Mobile phones	21.1%	38.30	181.23		
Desktop PCs	6.5%	39.93	614.62		
Laptop PCs and palm-top organisers	31.6%	51.06	161.55		
Flat screens	12.8%	11.44	89.64		
Total		140.74	1 047.05	**5 100**	**21 300**
Percentage of global demand (a) stemming from the four analysed products				**20.5%**	**4.9%**

Table 37: Global relevance of the selected products for the global demand for indium

Products	European market share, 2009	EU demand(a) in 2009 for Indium for respective products (tonnes)	Global demand(a) in 2009 for Indium for respective products (tonnes)	Global demand for Indium for all EEE products (EC 2010) (tonnes)	Total Global demand for Indium (EC 2010) (tonnes)
Mobile phones	21.1%	1.73	8.18		
Desktop PCs	6.5%	0.00	0.00		
Laptop PCs and palm-top organisers	31.6%	2.56	8.10		
Flat screens	12.8%	5.27	41.28		
Total		9.56	57.55	**420**	**568**
Percentage of global demand (a) stemming from the four analysed products				**13.7%**	**10.1%**

(a) Demand is defined as the quantity of material in the products put on the market. As such "demand" here assumes 100% production efficiency (see below).

The overall demand for metals in the EEE sector should also include materials used in production, but not appearing in the final product. For example for indium the USGS report states: "Sputtering, the process in which ITO is deposited as a thin-film coating onto a substrate, is highly inefficient; approximately 30 % of an ITO target material is deposited onto the substrate. The remaining 70 % consists of the spent ITO target material, the grinding sludge, and the after-processing residue left on the walls of the sputtering chamber.[33]"

Sputtering is a common technology for different metals which are used on surfaces, also for e.g. for ruthenium on hard drives. These kinds of production inefficiencies might be a major limitation in determining the share of demand that can be covered product recycling. Also, the recycling of so called new scrap and the efficient use of these resources in the production process also need to be taken into account. New scrap recycling rates are estimated to be quite high (about 70 %)[34], so that these 'losses' are mostly a statistical effect and not actual losses.

[33] http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2012-indiu.pdf, S. 74

[34] Wittmer et al. 2011

7 Socio-economic potentials of WEEE recycling

7.1 Economic value of metal losses

Table 38: Quantity and value of critical metal losses in mobile phones, desktop and laptop computers, flat screens and rechargeable batteries used in these product groups in EU in 2010.

	Recovered (kg)	Available (kg)	Losses (kg)	Value of losses 1000 Euro (a)
Ag	17 377	97 306	79 928	61 065
Co	134 261	1 338 710	1 204 449	32 129
In	0	4 660	4 660	2 824
Li	0	111 078	111 078	388 219
Ta	0	53 189	53 189	3 564
Te	26	1 868	1 842	334
W	0	56 636	56 636	20
Au	3 793	28 301	24 508	1 010 108
Be	0	817	817	578
Ga	0	1 347	1 347	540
Ge	0	787	787	863
Pd	1 096	8 186	7 090	118 303
Ru	50	263	212	579
TOTAL				**1 619 126**

(a) Based on 2011 commodity prices (London Metal Exchange Pricing and Data, 2011)

7.2 WEEE and employment

Increasing the recycling rates for waste electronic and electrical equipment (WEEE) not only protects the environment and saves resources, but it also offers substantial employment potentials in a green economy: "Material recycling from waste creates 5 to 7 times more jobs than disposal by incineration and 10 times more jobs than disposal in landfills."[35] According to the Commission's Thematic Strategy on waste prevention and recycling, the waste management and recycling sector in the EU25 already provides 1.2 to 1.5 million jobs. Based on recycling figures and experiences from Germany (Remondis, 2005) and Switzerland (Sinha-Khetriwal 2005), it is assessed that one job in the whole recycling chain is created for every 70 to 300 tonnes of WEEE collected (taking into account collection, dismantling, pre-processing and smelting). If WEEE collection is increased from 30 % to 65 % of that placed on the market, then the amount will increase in the EU from about 3.1 million to 6.5 million tonnes. This is assessed to create a minimum of 12 000 new jobs. It is estimated that a company engaged in WEEE recycling with a turnover of EUR 5 million

[35] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SEC:2008:2933:FIN:EN:PDF, S. 49

will provide 30 jobs in its own company and creates 70 new jobs in associated companies[36]. Furthermore, a greater emphasis on the qualitative and labour-intensive part of the recycling of critical metals (dismantling and pre-processing), would result in an even larger increase in the number of jobs created. The estimated growth rate for the generation of WEEE of 3-5 % per year should also be taken into account, which could mean a doubling of the job potential within the next 15 years.

Improved collection rates would also have positive impacts on the market for re-use. Reuse of refurbished WEEE has positive social impacts: the sector is already employing 40 000 people and engaging 110 000 volunteers in Europe, mainly working on WEEE (often these were long-term unemployed, people with disabilities or people at risk)[37].

The average costs for separate collection and treatment of WEEE in EU in 2009 was about 300 Euro per ton[38], this includes direct costs for the collection, transport and treatment as well as operational costs for monitoring and administration[39]. Incineration or disposal of WEEE according to EU environmental standards costs from 40 to 100 Euro per tonne including landfill tax (CEWEP, 2011). Recycling costs differ dramatically between the different WEEE product groups: They are extremely high for products like energy saving lamps containing hazardous substances, but for some categories – like large household appliances or mobile phones – the revenues from recovered secondary raw materials exceed the costs of the separate collection and treatment. With rising amounts of collected WEEE, the costs per tonne are expected to decrease: "Economies of scale in collection and treatment are likely to reduce costs per tonne; technological development of treatment operations is likely to further reduce treatment cost."[40]

According to the implementation of the principle of extended producer responsibility in the WEEE directive, producers have to contribute to the financial cost of the end-of-life phase of their products. Comparing the turnover of the EEE sector to estimated costs for the collection and treatment impacts of WEEE, the financial impact of collection and treatment of WEEE appears likely to be minimal as they account for well below 1 % of turnover, although for specific products and producers this may not be the case. With regard to collection and recycling targets in the WEEE Directive (EU-Commission, 2002), the European Commission stated that "it appears unlikely that WEEE policy will have a significant impact upon profitability". It has been estimated that prices for EEE could increase by an average of 1 %.[41]

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[36] http://circa.europa.eu/Public/irc/env/weee_2008/library?l=/further_studies/abschluss-bericht/_DE_1.0_&a=d

[37] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SEC:2008:2933:FIN:EN:PDF, S. 49

[38] The overall gross cost composition can be estimated to be costs for collection (17%), logistics (29%), treatment (33%) and additional costs (21%).

[39] Cf. WEEE Forum Key Figures 2010

[40] http://ec.europa.eu/environment/enveco/waste/pdf/waste_management_employment.pdf, s. 38

[41] http://ec.europa.eu/environment/enveco/waste/pdf/waste_management_employment.pdf, s. 38

8 Conclusions

8.1 The main results

8.1.1 Selection of critical metals and the relevant product groups

The first task has been to define the critical metals with a special importance for Electric and Electronic Equipment (EEE). We have defined the metals not only by looking at scarcity or the supply risks but also on the economic relevance of the metal, including growth in demand and price development. By using this criterion, we have ended up with other metals than just exclusively rare earth metals. Many of the selected metals are in line with "the 14 critical raw materials for the EU" defined by the EU Commission in its report from 2010 (EU-Commission, 2010).

The critical metals included in this report are: Silver, Cobalt, Indium, Lithium, Tantalum, Tellurium and Tungsten, which all fulfil the defined criteria. Gold, Beryllium, Gallium, Germanium, Palladium and Ruthenium are also included but do not fulfil all of the criteria. After the selection of the metals, we assessed which type of EEE will be able to contribute the largest amount of critical metals. Based on an assessment of the products' use of the critical metals and the economic importance of the products measured as sales volumes, the following products were selected for further study: Mobile phones; desktop computers; laptops and notebooks; TV and flat screen monitors; solar energy modules and rechargeable batteries in WEEE.

8.1.2 The collected and the potential WEEE from the selected product groups

Based on the total amount of collected WEEE in the EU in 2007 and 2008 and the composition of collected WEEE in Germany, the quantity of waste mobile phones, desktop computers, laptops and notebook, LCD TV, LCD monitors, plasma TV, solar energy modules and rechargeable batteries collected in the EU in 2007 and 2008 was estimated.

It is estimated that approximately 81 000 tonnes of waste of these products was collected in 2008, while it is calculated that approximately 254 000 tonnes of waste of these products was generated in the same year, (cf. table 12 and table 14).

Of the 254 000 tonnes generated in 2008, it is assessed that about 2 000 tonnes were critical metals, around 85% of which was cobalt (cf. table 32). Of this potential available amount it is assessed that less than 200 tonnes or only 9 % was recovered in 2008. Around 90 % of the recovered material was cobalt, but smaller amounts of silver, gold, palladium, ruthenium and tellurium were also recovered.

8.1.3 Reasons for the extremely low efficiency recycling rates of the critical metals

Extremely low overall recycling efficiencies are responsible for the low recycling of the critical metals. This is caused by:

- Missing collection of the selected WEEE products groups: only 1/3 is reported as collected;
- Export of used EEE products or illegal export of WEEE out the EU. At least 12 000 tonnes of old computers are assed to be shipped out of the EU to non-OECD countries;
- High losses during pre-processing, depending on whether manual or mechanically dismantling is applied. Manual pre-processing can provide over 90 % recycling metal rate for many of the selected products groups, whereas the mechanical process for most metals only give recycling rate between 0 - 60 %;
- Although the recycling rate in end-processing (smelting) is very high (90 to 95 %) for certain metals such as silver, cobalt, tellurium, gold, palladium and ruthenium,

the rate is 0 % (i.e. none of the material is recovered) for 7 of the selected 13 critical metals;
- The recycling rate of WEEE is poor for some of the metals because the whole recycling process (dismantling, pre-processing, end-processing) focuses and is tailored toward the extraction of bulk materials, and satisfactory dismantling,- pre-processing- and end-processing technologies are not present;
- There are thermodynamic-limits to the recycling of certain metals if jointly contained in complex mixes with other elements.

These reasons for the low overall recycling rates indicate that increasing the recycling efficiency will require more than the further development of technology solutions. Legal initiatives to increase recycling rates, improve process quality and hinder export out of the EU of WEEE are also required. Such initiatives are partly taken in the new EU WEEE Directive, which came into force in 2012.

8.1.4 Future amounts of critical metals from the selected WEEE product groups

Solar energy modules contain high quantities of indium as well as – depending on the type - silver and tellurium. Since it will be more than 25 years before the majority of installed PV modules will become waste, PV panels have not been included in the, as these only address the period until 2015. However, in a longer time perspective, recycling of solar panels will be an important source for certain critical metals, especially indium.

EU sales figures have been estimated for the period 2000 to 2010 using data from Eurostat's Prodcom database from 2007 to 2009; German sales figures from 2005 to 2010; Portuguese sales figures from 2007, 2008 and 2010; and the development of GDP.

By using life-span distribution figures from a Nordic study, the amount of generated WEEE linked to the selected products groups has been calculated for 2010 and 2015. Excluding waste of solar energy modules, the waste from the selected product groups will increase from 254 000 tonnes in 2008 to 338 000 tonnes in 2010 and 639 000 tonnes by 2015. That is to say the amount of WEEE will increase by a factor of three, and the quantity of critical metals in that WEEE will be almost 3 000 tonnes by 2015.

Cobalt will still constitute the largest share; about 2 500 tonnes. This is equivalent to approximately 12 % of the global demand for cobalt. The recycling of the other metals, for example indium, represents a lower percentage of demand.

8.1.5 The potential amounts of critical metals from recycling compared to the demand

It has not been possible to obtain figures for the total EU demand for the selected critical metals used by the European EEE sector. However, there are figures for the global EEE driven demand of the metals. These figures can be compared with the potential EU amounts of critical metals coming from WEEE. It shows that the potential available amount of the metals in the selected WEEE product groups in 2008 could cover about 12 % of the total global EEE driven demand for tellurium and about 16 % for of the global EEE driven demand for palladium. For the other metals, the coverage of the global EEE driven demand is below 10 %. Some are surprisingly low, such as indium, for which the potential recoverable supply in European EEE would cover less than 1 % of the global EEE driven demand for the metal. Relating the amount of potential recyclable metals in 2015 to the demand in 2008 gives a more positive result. For four of these metals (cobalt, tantalum, tellurium, gold and palladium) the coverage is more than 10 %.

The results highlight the uncertainties in the assumptions we have in our model regarding metal content, composition of the collected WEEE, collection rates etc. The results can also

reflect that some of the EEE products used in industry, which are only sold in a minor volume, have in fact rather a high content of the selected critical metals.

Although the calculated figures indicate that the potential available amount of critical metals in WEEE falls well short of anticipated demand, it can be argued that recycling of these metals is nevertheless of increasing importance.

8.1.6 The economic value of recycling of critical metals in WEEE and creation of new jobs

The missing recycling of critical metals also results in economic losses. It estimated that the losses of the 13 selected critical metals are equivalent to a value of more than 1.6 billion Euros.

Increased recycling of WEEE would also create more jobs. The new WEEE Directive (EU-Commission, 2012) aims to increase the collection rate of WEEE to 65 % of what is put on the market, i.e. an increase from 3.1 million to 6.5 million tonnes. This is assessed to create a minimum of 12 000 new jobs spread throughout the whole WEEE sector (i.e. this figure covers not only recycling of critical metals).

8.1.7 Better data quality and availability is required

It has been more difficult than expected to get free access to detailed sales figures about the different selected product groups. It is possible to purchase information on sales figures, but the price is beyond the limited budget of this project.

As shown in chapter 6, the content of critical metals per kg product is normally very low, i.e. less than one gram per kilo. However, it is very difficult to obtain information on the specific quantity of critical metals in EEE products or components. We have requested such information from different producers but we have received rather limited answers. We initially thought this was due to competition grounds and business secrecy, but in fact producers are often simply not aware of the exact content of the products and components. This can be because some components are produced by a subcontractor, but also that many critical metals are also not strictly regulated. Therefore, there is less of a focus on documenting the use of the critical metals compared to, for example, the use of hazardous substances.

Much in the same way it has been difficult to obtain detailed information on the WEEE collection, it has been a challenge to clearly identify the selected product groups. For example, TV sets contain different amounts of critical metals depending on whether the focus is on old TV sets which use CRT technology, or new TV set based on LCD technology. If recycling is to contribute to the future supply of critical metals, it is necessary to work with more transparency on the types and volumes of the collection of the concerned WEEE product groups.

Based on the experiences obtained in this study it is clear that, for the EU is to increase the recycling of critical metals in WEEE, we need access to improved data on quantities of critical metals contained in the different products in the EU. This includes understanding where the metals are mainly located in various components, an understanding of the composition of collected WEEE, and an accurate figure on how many of these products are being sold in the EU. The lack of this information combined with poor collection rates and the threat of (illegal) exports from Europe creates a risky investment environment for recycling infrastructures; this is a barrier that has to be overcome if we are to achieve improved levels of recycling.

8.2 What can be done in order to improve the present situation

The revised WEEE Directive (EU-Commission, 2012), contains a variety of improvements that should have a positive impact on the possibilities for better recycling of the critical metals in WEEE.

- Critical raw materials are now included in the purpose of the Directive;
- A new minimum collection rate of 45 % to be achieved within four years and a collection rate of 65 % after 7 to 9 years after the Directive came into force. The rate is calculated as a percentage of the average weight of EEE placed on the market in the three preceding years;
- Initiatives to better distinguish between used products (EEE) and waste (WEEE). Any holder of used EEE wanting to make transboundary shipments must provide documentation recording the testing of functionality of the used EEE;
- European standards for the collection, storage, transport, treatment, recycling and repair of WEEE as well as its preparation for reuse (cf. Annex VIII);
- Such amendments are important, but additional initiatives will have a positive influence in order to increase the amount of recycling of critical metals in WEEE.

Possible improvements are indicated and discussed below. Some of them show how the new WEEE Directive's articles could be implemented in practice; others are more original ideas[42].

Beyond this regulative framework, the analyses and expert workshop of this project shows that the crucial point in improving the recycling of critical metals in WEEE will be an integrated optimization of the whole value chain – including product design, collection, dismantling, pre-processing and smelting. Technical improvements in one of these steps offer limited results if weaknesses in other parts of the chain are not rectified.

New instruments and regulations enabling improved cooperation and exchange of information between the different actors will be required to facilitate this management of the entire value chain. Transaction costs for the gathering of reliable information seem to be a relevant barrier for circular flows of critical metals in WEEE, despite existing economic incentives for some metals due to rising raw material prices and relevant employment potentials.

8.2.1 Product design

Article 15 of the WEEE Directive sets the framework for the exchange of information between producers and recyclers: "In order to facilitate the preparation for reuse and the correct and environmentally sound treatment of WEEE, including maintenance, upgrade, refurbishment and recycling, Member States shall take the necessary measures to ensure that producers provide information free of charge about preparation for reuse and treatment in respect of each type of new EEE placed for the first time on the Union market within one year after the equipment is placed on the market" (EU-Commission, 2012).

WEEE experts consulted in this project confirmed that this cooperation works very inefficiently regarding the recycling of critical metals for several reasons:

[42] A number of these ideas are also contained in a report, released in 2010, with 10 recommendations to improve access to critical raw materials (Öko-Institut and Eurometaux, 2010) In additions to the points hereafter the reports proposes a certification scheme for end-processors in order to secure high quality recycling, focussing on high yields for a broad range of metals as well on environmental and energy performance.

- Often the product- or component- producers themselves have insufficient information on content and location of specific critical metals due to complex supply chains. The original equipment manufacturer focus on functionality and legal requirements like REACH and ROHS[43] when ordering their components – as do the component producers when ordering specific parts[44]. In this global network, the material composition of specific products can change on a daily basis depending on changes in raw material prices.
- Producers are often not aware about the kind and structuring of information the recyclers on the different levels (dismantling, pre-processing etc.) need in order to be able to localize the critical metals in a discarded product or component. Often they also keep this kind of information confidential because competitors could use material composition to deduce technical innovations.
- Building up such a database of information is additionally complicated by different national interpretations of the WEEE Directive. E.g. the German ElektroG qualifies this regulation narrowing it down on information needed "for the purposes of complying with the provisions of this Act" (§13.6 ElektroG) – which does not include the recycling of critical metals. Instead of making a product information data base at national level it seems much more relevant to do it at EU or European scale.

WEEE Network

The Commission could support the initiation of such a product information data base or the establishment of an EU Network for EEE producers and WEEE treatment enterprises in order to improve recycling of WEEE. Within this network, information shall be shared about how to combine materials and what to do to substitute or reduce specific raw materials including critical metals in order to enable the optimal resource recycling from the WEEE treatment. The network could be built up on existing projects like the 'Solving the Ewaste Problem Initiative' (StEP[45]) which already includes a task force on ReDesign or instruments like the 'RecyclingPassport' developed for EEE producers[46].

RFID chips

As a technical solution in order to improve the flow of information between producers and the actors in the recycling chain, complex electronic products like PCs or flat screens could be equipped with a RFID (Radio-frequency identification) tag containing specific information for the disassembly of the product, content of specific materials and their location. This technology uses radio waves to transfer data from an electronic tag attached to an object through a reader for the purpose of identifying and tracking the object. RFID tags can be read from several metres away and beyond the line of sight of the reader. In contrast to conventional bar codes it allows an almost-parallel reading of tags.

[43] Skeates 2011: ETC workshop presentation.

[44] Lauridsen/ Joergensen 2010 http://www.sciencedirect.com/science/article/pii/S0048733310000351,

[45] www.step-initiative.org

[46] http://www.recyclingpass.net/index.php?id=673&no_cache=1&sword_list[]=pass

RFID tags are already used in the waste management sector with promising results. They can also be used as an open loop solution by different actors along the whole product life cycle, e.g. as anti-theft device. The potential benefits of using RFID tags in the recycling of WEEE has been proved in different research projects[47], specific reading devices have already been developed for sorting waste electronic products[48].

Ecodesign

As economic incentives will not be sufficient for the recycling of all critical metals in WEEE, legal requirements should be considered. In 2005, the European Union released the Ecodesign Directive (Directive 2005/32/EC) which establishes a framework for defining concrete requirements for individual products through so-called implementing measures. It originally focused on environmental standards for energy using products but will be reviewed in 2012 and could be broadened in its perspective.

Consequently, in addition to energy efficiency issues, other ecodesign aspects such as material efficiency could gain higher importance[49]. With regard to EEE requirements for expanding the life span of products, the choice of materials, recyclability, ease of dismantling components relevant for critical metals (circuit boards, batteries, magnets etc.), and ease of repair for example, could be integrated to reduce the demand for critical metals or to improve their recycling. This is already foreseen in Annex X of the new WEEE Review proposal).

8.2.2 Collection of WEEE

The revised WEEE Directive introduces a new product category 'small IT and telecommunication equipment'. Collection according to this new structure would support the recycling of critical metals, which are especially concentrated in these products. Nevertheless, many used products are not available for recycling because they are horded within households. This is especially relevant for small appliances like mobile phones. The hording itself, of course, does not cause any environmental damage, but the recycling of the critical metals contained would reduce the demand for primary resources. Product specific deposit and refund schemes for small EEE could provide an incentive to bring back used products. A graduated deposit fee based on the products environmental performance could be used to promote greener products.

8.2.3 Export of WEEE outside EU

The illegal export of waste electronic products has been recognised as a major cause of losses of critical metals due to insufficient recycling infrastructures in the destination regions. The review of the WEEE Directive has taken up this issue and includes a shift in the burden of proof for the exporters. This approach could be fostered by the following measures.

Differentiation between used and waste products in the export statistics

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[47] http://www.uni-kassel.de/upress/online/frei/978-3-89958-804-0.volltext.frei.pdf, P. 59ff.

[48] RFID chips however, contain silver themselves and a mass application of RFIDs can have a significant impact on silver demand. Therefore RFIDs should be not be placed e.g. on steel, aluminum or plastic casings but on components who will be recycled in a process that is suitable for silver recovery (e.g. circuit boards, copper parts).

[49] These aspects have been analyzed in the MaRess-Project: http://ressourcen.wupperinst.org/downloads/MaRess_AP14_6_ExecSummary.pdf, P. 11

The evaluation of statistics and databases has shown that meaningful information on the export of used electrical and electronic equipment can only be prepared with a lot of time and effort, if at all. In order to improve information from the further monitoring of the development of exports of such appliances, a differentiation in the statistics between new and used appliances is important, as shown by the example of End of Live Vehicles: it helps to estimate the overall amount of exports and allows identifying relevant origins and destinations of WEEE exports[50]. European statistics should therefore differentiate for relevant exported appliance types such as monitors, televisions, refrigerators between new and used appliances by introducing appropriate codes in the combined nomenclature. Worldwide harmonisation is recommended as a longer-term prospect.

Easier differentiation between used and waste products in export controls
Important legal regulatory areas which concern the exporting of used appliances are the differentiation between waste and non-waste and the regulations concerning the export restriction of appliances which do not meet certain minimum requirements. Results in recent research projects, in cooperation with the parties controlling exports, have shown that a simple legal basis for distinguishing between appliances that may be exported in the product regime and those which should be exported in the better-monitored waste regime, is considered to be essential[51]. Although there is a clear trade-off between simplicity of requirements and unwanted consequences, like the prevention of re-use of some used products in other countries, it is necessary to make this distinction easier due to very limited personal resources of the customs authorities, particularly in ports. This could be achieved by the following very pragmatic measures.

1. Specification for packaging requirements
Appendix 1 of the Correspondents' guidelines on Shipments of Waste Electrical and Electronic Equipment (WEEE) states that IT equipment may be defined as waste if it has "an insufficient packaging to protect it from damage during transportation, loading and unloading operations"[52], this has also been included in the Appendix of the proposal for a Directive of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE). These requirements for proper packaging should be defined more precisely in a product-specific way. This can be done though in subordinate regulations.

[50] Cf. http://ewasteguide.info/files/Sander_2010_Oekopol_EN.pdf, P. 98
http://eea.eionet.europa.eu/Public/irc/eionet-circle/etc_waste/library?l=/working_papers/shipments290208pdf/_EN_1.0_&a=d, P 64
[51] Cf. http://ewasteguide.info/files/Sander_2010_Oekopol_EN.pdf, S. 101
[52] http://ec.europa.eu/environment/waste/shipments/pdf/correspondents_guidelines_en.pdf, S. 6

With regard to cathode ray tube (CRT) screens, which might be the most urgent problem with regard to volumes and hazardous content, exports could be obligated to use re-usable specific transport packaging for every screen. These boxes cost about 15 Euro and even if they can be used several times they cut off incentives to export waste products just in order to avoid disposal costs within the EU[53].

Figure 7: Padded packaging for screens

Source: Ratioform[54]

2. Special burden of proof for products older than four years

Annex IV of the revised WEEE Directive, regarding shipment of used EEE, states that Member States shall, in cases of suspected waste products, request evidence of evaluation or testing every item. Article 22 suggests that additional rules on inspections be established in order to secure uniform conditions for the implementation of Annex IV.

One possibility of facilitating practical inspections could be to implement a rule requiring that EU exports of used EEE have to provide specific evidence of total functionality if the product is older than four years. Such an initiative would provide an incentive to reduce illegal shipments out of the EU.

International WEEE partnerships

Given the significant amounts of legal and illegal exports of used and waste electronic products to developing and emerging economies, technology and knowledge transfer should be promoted to help these countries manage the eventual waste.[55]. These countries are usually characterised by very high collection rates, with small industries that can undertake the dismantling and pre-processing activities of the recycling chain, but completely lack the necessary final end-processing recycling infrastructure (see Yu et al. 2010). This could open up significant win-win potentials if the precious metals, like those on circuit boards, are supplied to the internationally networked end-processing facilities instead of to a backyard recycling operation, which pose severe risks to health and the environment. It is also worthy of note that the revenues from recycling significantly exceed the additional transportation costs (see Hagelueken 2010).

In light of the need for a reliable regulative framework and based on the deficits observed, and the limits of direct regulation regarding the recycling of exported WEEE, a so-called

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[53] Cf. http://ressourcen.wupperinst.org/downloads/MaRess_AP2_3.pdf, S. 190

[54] http://www.ratioform.at/verpackung/Fuellen-Polstern-und-Schuetzen/Schaumfolien-Noppenschaum-und-Schaumpolster/Schaumverpackung-Mbrace-fuer-Laptops-und-Displays/#breadcrumb

[55] Cf. Hagelüken/ Meskers 2010
http://www.preciousmetals.umicore.com/PMR/Media/sustainability/show_complexLifeCycles.pdf

covenant could enhance material efficiency and resource conservation in this field of action[56]. Covenants represent a combination of elements of direct governmental regulation and self-regulation by industry in specific countries relevant for the export and import of ELVs. In principle, such a covenant may be characterised by the following elements:

(1) Industrial sectors commit themselves to achieving long-term goals;
(2) These goals are negotiated in cooperation with the responsible authorities of the public sector;
(3) In return, the public authorities commit themselves to creating appropriate framework conditions and to omitting further direct regulatory measures for the contract period and;
(4) Covenants are concluded as private law contracts between all parties involved. Such contracts include both sanction mechanisms in case the stipulated goals are not achieved, and options to adapt the terms and conditions in case of changing framework conditions. Nevertheless, covenants raise a variety of legal issues, e.g. possible conflicts with the Basel Convention or WTO regulations. Possible solutions have been discussed in the MaRess-project, the Kimberley process on blood diamonds might serve as a model for some of these aspects[57].

[56] Wilts et al. 2011
[57] Wilts/ Bleischwitz/ Sanden 2010

9 References

Anreee, 2011: Associacao national para o registo de equipment electricos e electronicos, Portugal.http://anreee.pt/index.php?content=112.

BFE, 2011: Branchen Forbruger Elektronik, Denmark http://forbrugerelektronik.dk/forbrugerelektronik/presse/markedsinfo/).

Bio Intelligence Service, 2011: Study on photovoltaic panels supplementing the impact assessment for a recast of the WEEE Directive, April 2011.

Böni, H.; Widmer, R. (2011): Entsorgung von Flachbildschirmen in der Schweiz. Schlussbericht, St. Gallen.

Broadcastengineering, 2012: http://broadcastengineering.com/news/DisplaySearch_Worldwide_TV_Market_by_Technology_2004-2013_100323.jpg.

Buchert, M.; Manhart, A.; Bleher, D.; Pingel, D. (2012): Recycling critical raw materials from waste electronic equipment. Commissioned by the North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection.

Carsten Eichert, C./ Kernbaum, S./ Solenthaler, C. (2008): WEEE treatment by vertical hammer mill – technological results, economic value and ecological implications. http://ewasteguide.info/files/Hammer_Mill-LCE_Sydney_2008_0.pdf .

Chancerel, P. (2010): Substance flow analysis of the recycling of small waste electrical and electronic equipment. Institut für Technischen Umweltschutz, ITU-Schriftenreihe 09/2010, Berlin.

Chancerel, P.; Bolland, T.; Rotter, V.S. (2010): Status of pre-processing of waste electrical and electronic equipment in Germany and its influence on the recycling of gold. Waste Management & Research.

Chancerel, P.; Meskers, C.E.M.; Hagelüken, C.; Rotter, V.S. (2009):Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. Journal of Industrial Ecology 13 (5), 2009: 791-810.

Chuo Kankyo Shingkikai (Central Council on the Environment). 2011. Material 2 "About the Ways of Organising Recycling Systems for Small Electrical Home Appliances." Appendix to Rererence 1. Content of useful metals in Small Home Electrical Home Appliances (circuit board, components, break-down of materials).

Cui, J.; Forssberg, E. (2003): Mechanical recycling of waste electric and electronic equipment: a review. Journal of Hazardous Materials B99, 2003: 243–263.

Cui, J.; Zhang, L.(2008): Metallurgical recovery of metals from electronic waste: A review. Journal of Hazardous Materials 158, 2008: pp. 228-256.

Drechsler, C. (2006): Mechanische Verfahren zum Recycling von Elektronikschrott mit Rotorshredder und Rotorprallmühle. In: Aufbereitungstechnik Vol. 47, Nr. 3.

EAR, 2011: Stiftung Elektro-altgeräte register, Germany. http://www.stiftung-ear.de/service_und_aktuelles/kennzahlen/inputmengen_je_geraeteart_a.

EEA, 2012: Movements of waste across the EU's internal and external borders. http://www.eea.europa.eu/publications/movements-of-waste-EU-2012

Eichert, C.; Kernbaum, S.; Solenthaler, C. (2008): WEEE treatment by vertical hammer mill. International Conference on Life Cycle Engineering (LCE) 15, Sydney.

Environment Agency-England & Wales, 2011: Study into the feasibility of protecting and recovering critical raw materials through infrastructure development in the South East England. http://www.environment-agency.gov.uk/static/documents/Business/EPOW-recovering-critical-raw-materials-T5v2.pdf.

EPBA, 2010. Sustainability Report 2010: Looking back, looking ahead. In http://www.epbaeurope.net/Sustainabilityreport.html.

ETC/SCP, 2010: Transboundary Shipments of Waste in the European Union – Availability of data, methodologies and information on their drivers and environmental impacts http://scp.eionet.europa.eu/publications/Transbound%20data%20report.

ETC/SCP, 2011: Recycling of Critical Metals in WEEE-Developing a Methodology. Draft paper not published.

EU-Commission, 2002: DIRECTIVE 2002/96/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 January 2003 on waste electrical and electronic equipment (WEEE) http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2002L0096:20080321:EN:PDF

EU-Commission, 2005: Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and The Committee of the Regions. Thematic Strategy on the use of natural resources. COM (2005) 670 final. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0013:FIN:EN:PDF

EU-Commission, 2010: Critical raw materials for the EU http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report_en.pdf.

EU-Commission, 2012: DIRECTIVE 2012/19/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 4 July 2012 on waste electrical and electronic equipment (WEEE). http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:EN:PDF.

Eugster M., Hischier R. and Duan H. (2007). Key Environmental Impacts of the Chinese EEE-Industry A Life Cycle Assessment Study. St. Gallen, Switzerland, EMPA, Materials Science and Technology: 1-90.

Eurostat, 2011. WEEE Collection data. Addressed August 2011. http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastestreams/weee

Eurostat's, Prodcom database, 2011:

Eurostat, 2012: Annual national accounts. http://epp.eurostat.ec.europa.eu/portal/page/portal/national_accounts/data/main_tables.

Financial Times, 2012: http://www.ft.com/cms/s/2/08a4f6ac-c614-11dd-a741-000077b07658.html#axzz1kHcU3ex6.

Finland, 2011: Waste Flows in Finnish Producer Responsibility System– Case WEEE and Portable Batteries and Accumulators, September 2011 JYVÄSKYLÄ UNIVERSITY SCHOOL OF BUSINESS AND ECONOMICS - http://www.serty.fi/uploads/jase-nille/materiaalit/Tutkimuksen_tiivistelm%C3%A4_englanniksi.pdf.

Fröhlich, G. (2009): Entsorgung von Elektro- und Elektronikgeräten in der Praxis. In: Thomé-Kozmiensky, K.J./ Goldmann, D. (Hrsg.): Recycling und Rohstoffe. Band 2. Neu-Ruppin.

Gartner 2011: http://www.gartner.com/it/page.jsp?id=1543014.

Germany, 2011: Ökopol. 2011. WEEE FLOWS IN GERMANY, Short analysis for HEWLETT PACKARD COMPANY.

GFU, 2011: Gesellschaft für Unterhaltungs- und Kommunikationselektronik, Germany http://www.gfu.de/home/marktzahlen/markt.xhtml.

Gmünder, S. (2007): Recycling - From Waste to Resource - Assessment of optimal manual dismantling depth of a desktop PC in China based on eco-efficiency calculations. Diploma thesis, Eidgenössische Technische Hochschule Zürich, Zürich.

Gößling-Reisemann, S. (2008): Entropy analysis of metal production and recycling. In: Management of environmental quality.

Hagelüken C. and Meskers C. E. M. (2010): Complex Life Cycles of Precious and Special Metals; in: Graedel T. E. / van der Voet E. (Ed.): Linkages of Sustainability. From the Strüngmann Forum Report. MIT Press, 163-197.

Hagelüken, C. (2008): Opportunities & challenges to recover scarce and valuable metals from electronic devices, Presentation, OECD-UNEP Conference on Resource Efficiency, Paris, 24.04.2008.

Hagelüken, C., Meskers, C.E.M. (2009): Technology challenges to recover precious and special metals from complex products. R'09 Twin World Congress and World Resources Forum, Davos, Switzerland, September 14-16, 2009.

Hagelüken,C and Corti, C., 2010: 'Recycling of gold from electronics: Cost-effective use through "Design for Recycling', Gold Bulletin, Volume 43, N03, 2010. http://www.springerlink.com/content/16807h2311171379/.

Hagelüken C. and Meskers C. E. M. (2010): Complex Life Cycles of Precious and Special Metals; in: Graedel T. E. / van der Voet E. (Ed.): Linkages of Sustainability. From the Strüngmann Forum Report. MIT Press, 163-197.

Hagelüken, C. (2011). Personal communication (29.08.2011).

Hagelüken, C. (2012). Personal communication (07.06.2012).

ICD, 2010: Wordwide quarterly PC tracker August 2010.

IGF (##): Abschlussbericht 16040.

Hischier R., Wager P. and Gauglhofer J. (2005). "Does WEEE recycling make sense from an environmental perspective?" Environmental Impact Assessment Review 25(5): 525-539.

Jacobsen, H., 2012: Personal information from Henrik Jacobsen, El-Retur on 3 April 2012.

Janz, A. (2010): Effect of the removal of hazardous substances from WEEE on emissions of treatment and recycling. October 6th 2010, Chania.

JCN Network (2005): Sharp Uses LCD Panels to recycle Indium. http://www.japan-corp.net/Article.Asp?Art_ID=10141, 24.05.05 (accessed 22.08.2011).

JOGMEC (Japan Oil, Gas and Metals National Corporation). 2008. Working Paper on the Development of Efficient Recovery Systems of Less Common Metals. 2007. (in Japanese).

Johnson Matthey (2009): Platinum 2009. Hertfordshire.

Jorgenson, J. D. / George, M. W. (2005): Mineral Commodity Profile: Indium. Open-File Report 2004-1300, U. S. Geological Survey, Reston, Virginia.

Kawaguchi, Y. (2008): Recyceltes Home Cinema. *Wissenschaft und Technik*, Vol. 9, 46-49.

Kida, Akiko, Shirahase, Tomoko and Kawaguchi, Mitsuo. 2009. Metal Contents including precious metals in waste personal computers. Material Cycles and Waste Management Research 20 (2), 59-69 (in Japanese).

Koomey J. (2008). "Worldwide Electricity Used in Data Centers." Environmental Research Letters(IOP Publishing Ltd.): 1-9.

Koomey J.G., Berard S., Sanchez M. and Wong H. (2009). Assessing Trends in the Electrical Efficiency of Computation over Time, Lawrence Berkeley National Laboratory and Stanford University; Microsoft Corporation; Intel Corporation: 1-47.

London Metal Exchange Pricing and Data, 2011: https://www.lme.com/en-gb/pricing-and-data/

Meskers CEM, Hagelüken C, Salhofer S, and Spitzbart M. (2009): Impact of pre-processing routes on precious metal recovery from PCs. In: Proc. of European Metallurgical Conference EMC 2009, 28 June–1 July 2009, Innsbruck, Austria, Clausthal Zellerfeld.

MOE & METI (Japanese Ministry of the Environment and Ministry of Economy, Trade and Industry). 2010. Reference 3. Result of the Study of Metal content of Small Home Electrical Home Appliances.

Lehner, Theo (2011): Personal communication from Boliden to ETC/SCP, 02.09.2011.

Meskers, C. E. M. (2010): Challenges in closing the loop for special metals. Presentation at the MMTA´s International Minor Metals Conference, London 26-28 April 2010. Umicore Precious Metals Refining.

Meskers, C. E. M., Vandenbroeck K., Vliegen J., De Ruijter I., Dalle T., Rigby P. (2010): Recycling Technologies to Close the Loop for PV Materials; in: Proceedings 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, Valencia: 3683–3687.

Meskers, C./ Hagelüken, C. (2009): The impact of different pre-processing routes on the metal recovery from PCs. In: R09.

Netherlands, 2012: The Dutch WEEE Flows. Study carried out by Huisman, J., van der Maesen, M., Eijsbouts, R.J.J., Wang., F., Baldé, C.P., Wielenga, C.A., 2012. http://www.wecycle.nl/uploads/futureflows/Press/Report_Dutch_WEEE_Flows.pdf.

Niederschlag E. and Stelter M. (2009): 145 Jahre Indium – Ein Metall mit Zukunft? *Erzmetall*, Vol. 62, Nr. 1.

Noël F. (1989): Indium and Indium Compounds; in: Ullmann´s Encyclopedia of Industrial Chemistry, Vol. A 14, 5th, completely revised edition; Weinheim, Basel, Cambridge, New York: 157-166.

Nordic Council, 2009: Method to measure the amount of WEEE generated. Report to Nordic council's subgroup on EEE waste. Nordic Council of ministers. http://www.norden.org/en/publications/publikationer/2009-548.

NRC (2008). Minerals, Critical Minerals and the U.S. Economy. National Research Council, Washington D.C., The National Academies Press.

OECD Environment Directorate (2010) a: Materials Case Study 1: Critical Metals and Mobile Devices. OECD Global Forum on Environment focusing on Sustainable materials Management, 25-27 October 2010, Mechelen, Belgium.

OECD Environment Directorate (2010) b: Materials Case Study 1: Critical Metals and Mobile Devices, Annexes. OECD Global Forum on Environment focusing on Sustainable materials Management, 25-27 October 2010, Mechelen, Belgium.

Oguchi, Masahiro. 2007. Study on analysis of lifespan distribution and product-based material flow of electrical and electronic products. Ph.D. Thesis. Yokohama National University (in Japanese with English figures and tables).

Oguchi, Masahiro, Murakami, Shinsuke, Sakanakura, Hirofumi, Kida, Akiko and Kameya, Takashi. 2011. A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. Waste Management. 31 (2011) 2150-2160.

Öko-Institut , 2012: Recycling kritischer Rohstoffe aus Elektronik-Altgeräten - LANUV-Fachbericht 38.

Öko-Institut and Eurometaux, 2010: Eurometaux' proposals for the raw materials initiative. http://www.oeko.de/publikationen/forschungsberichte/studien/dok/657.php?id=&dokid=1069&anzeige=det&ITitel1=&IAutor1=&ISchlagw1=&sortieren=&dokid=1069.

Ökopol , 2007: Study on the development of a take back and recovery system for photovoltaic products, 2007.

Ökopol (2010): Studie zur Weiterentwicklung der Produktverantwortung, study carried out on behalf of the Ministry for Environment and Climate Protection Lower-Saxony, Germany.

Optisort, 2012: Optisort AB, Gothenburg, Sweden. http://www.optisort.com/obs/.

Plepys A. (2004). The environmental impacts of electronics. Going beyond the walls of semiconductor fabs. Electronics and the Environment, 2004. ISEE 2004. Proceedings of the 2004 IEEE International Symposium on, Scottsdale, AZ, USA, Institute of Electrical and Electronics Engineers (IEEE).

PV Cycle, 2011: European Association for the Recovery of Photovoltaic Modules ANNUAL REPORT 2010 http://www.pvcycle.org/.

RWI, Fraunhofer ISI und BGR – BA für Geowissenschaften Rohstoffe (2006), Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen. RWI Projektberichte. Essen. http://www.rwi-essen.de/forschung-und-beratung/umwelt-und-ressourcen/projekte/93/.

Rüth E. (2009): Die Nullnummer. Indium ist wertvoll, unverzichtbar und knapp. In Deutschland wird es nicht recycelt. Warum? *Recycling Magazin*, Vol. 64, Nr. 10, 28-29.

Rüth, M. (2010): Über Bedarf und Beschaffung von Gallium, Indium, Germanium und Tellur. Vortrag an der Euroforum-Konferenz Technologiemetalle, Frankfurt, 21.-22.09.2010.

Salhofer, S./ Spitzbart, M./ Schöps, D./ Meskers, C./ Kriegl, M./ Panowitz, G (2009): Verfahrensvergleich zur Gewinnung von Wertstoffen aus Elektroaltgeräten. In: Bilitewski, B./ Werner, P./ Janz, A. (Hrsg.): Brennpunkt ElektroG. Tagungsband zur Fachtagung am 23. April 2009, Dresden.

Sander K. (2007). Studie zur Entwicklung eines Rückmahme- und Verwertungssystem für Photovoltaische Produkte. *http://www.pvcycle.org/fileadmin/pvcycle_docs/documents/publications/Studie_PVCycle_Download_17_de_270808.pdf*, accessed 16.08.2011.

Sander K. (2009). Wertvolle Rohstoffbasis. Müllmagazin, 01/2009, p. 23-29.

Shingkikai, 2011: Chuo Kankyo Shingkikai (Central Council on the Environment of Japan). Material 2 "About the Ways of Organising Recycing Systems for Small Electrical Home Appliances." Content of useful metals in Small Home Electrical Home Appliances (circuit board, components, break-down of materials).

SWICO Recycling, 2011: Disposal of Flat Panel Display Monitors in Switzerland, Final Report, March 2011. http://swicorecycling.ch/downloads/497/344540/swico_schlussbericht_e_2010.pdf.

Tolcin, A. C. (2009): Minerals Yearbook 2008: Indium [Advance Release] (December 2009). U. S. Geological Survey.

Van den Broeck K. (2010): Exploring the challenges in closing the loop for special metals. Presentation at the Metal Pages International Minor Metals Conference, Xiamen, 19-21 October 2010. Umicore Precious Metals Refining.

UBA, 2010: Transboundary shipment of waste electrical and electronic scrap. Optimization of material flows and control. Umwelt Bundes Amt, Deutschaland, 22/2010.

UBA, Germany, 2011: Material Efficiency and Resource Conservation (MaRess) program. Led by the Wuppertal Institute with funding support from the German Federal Ministry for the Environment (BMU) and the German Federal Environment Agency (UBA). http://www.basel.int/techmatters/e_wastes/germany-report-18May2010.pdf.

UBA, Germany, 2011: Batterierecycling in Deutschland: Rücknahme- und Verwertungsergebnisse 2009. In http://www.umweltbundesamt.de/abfallwirtschaft/publikationen/papier_batterierecycling_in_deutschland_ruecknahme_und_verwertungsergebnisse_2009.pdf.

UNEP, 2009: Schluep, M; Hagelueken, C; Kuehr, R; Magalini, F; Maurer, C; Meskers, C; Mueller, E; Wang, F (2009): Recycling - from e-waste to resources, Sustainable innovation and technology transfer industrial sector studies. UNEP-Report, Paris.

United Nations University, 2007: 2008 review of Directive 2002/96 on WEEE (page 60-65).

USGS (2008a): Mineral commodity summaries 2008: U.S. Geological Survey, 199 p.

USGS (2008): Material Use in the United States—Selected Case Studies for Cadmium, Cobalt, Lithium, and Nickel in Rechargeable Batteries. Scientific Investigations Report 2008–5141, Reston.

USGS (2009): U.S. Geological Survey Material Use in the United States—Selected Case Studies for Cadmium, Cobalt, Lithium, and Nickel in Rechargeable Batteries. http://pubs.usgs.gov/sir/2008/5141/sir-2008-5141.pdf.

USGS. 2011. Mineral Commodity Summaries 2011. Reston. http://minerals.usgs.gov/minerals/pubs/mcs/2011/mcs2011.pdf.

Willems, B.; Dewulf, W.; Duflou, J. R. (2006): Can large-scale disassembly be profitable? A linear programming approach to quantifying the turning point to make disassembly economically viable. International Journal of Production Research 44 (6), 2006: 1125–1146.

Williams E.D., Ayres R.U. and Heller M. (2002). "The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices." Environmental Science and Technology 36(24): 5504 -5510.

Williams E.D. and Deng L. (2008). Measures and trends in energy use of semiconductor manufacturing. 2008 IEEE International Symposium on Electronics and the Environment, Proceedings of, San Francisco, CA, The Institute of Electrical and Electronics Engineers, Inc. (IEEE).

Wilts, Claas Henning ; Bleischwitz, Raimund ; Sanden, Joachim:
Ein Covenant zur Schließung internationaler Stoffkreisläufe im Bereich Altautorecycling : Meilenstein zu AS 3.2 „Maßnahmen zur Ressourcenpolitik zur Gestaltung der Rahmenbedingungen“ ; Paper zu Arbeitspaket 3 des Projekts „Materialeffizienz und Ressourcenschonung“ (MaRess). - Wuppertal : Wuppertal Inst. für Klima, Umwelt, Energie, 2010 - (Ressourceneffizienz Paper ; 3.5).

Wittmer et al, 2011: Wittmer D., Scharp M., Bringezu S., Ritthoff M., Erren M., Lauwigi C., Giegrich J. Umweltrelevante metallische Rohstoffe : Meilensteinbericht des Arbeitsschrittes 2.1 des Projekts "Materialeffizienz und Ressourcenschonung" (MaRess); Teil 1, Abschlussbericht. Wuppertal Institute for Climate, Environment and Energy, Resource Efficiency Paper, vol. 2.1, Wuppertal 2011: 213. http://ressourcen.wupperinst.org/downloads/MaRess_AP2_1.pdf

WRAP, 2011: Market flows of Electronic Products & WEEE Materials. http://www.wrap.org.uk/category/materials-and-products/electrical-and-electronic-goods?page=6.

Annex I: Use of critical metals in EEE

Below, the main areas of application (product groups/components) of the twelve recommended and optional metals are described.

Beryllium
Beryllium is the second lightest metal (Vulcan 2008), which combines excellent stiffness-to-weight and strength-to weight ratios, an outstanding dimensional stability to temperature (Jaskula, 2010), a high melting point of 1 280 ˚C, resistance to acids and a high thermal conductivity (McNeil, 2005).

In addition to its favourable properties Beryllium is highly toxic and carcinogenic (Environment Agency UK, 2011) and its utilisation is connected with high processing costs (McNeil, 2005). Therefore Beryllium is mainly used for military purposes and only in small quantities in the civilian sector (EC, 2010a). But its thermal and electric conductivity makes it particularly significant for EEE. That is the reason why approximately 40 % of beryllium is used for electronic equipment, domestic appliances as well as electronics and IT (e.g. computer chip heat sinks (Jaskula, 2010)) (EC, 2010a).

Especially important for the EEE sector are high-strength beryllium-copper alloys, which are utilised for telecommunications and IT applications, particularly for electrical contacts and connectors in cell phones and computers (Vulcan 2008). Further contributions to EEE include beryllium-aluminium alloys for the manufacturing of hard disc drives and beryllium oxide ceramics, used in heat sinks (McNeil 2005) as well as for the production of concentrated photovoltaic cells[58] (Knudson 2008). In addition to this Beryllium functions as a luminescent material, contained in TV sets (Behrendt et al. 1998).

Cobalt
Cobalt is a very hard metal, which retains its strength at high temperatures. It has low thermal and electrical conductivities, but is ferromagnetic, which means that it can be magnetised and maintain its magnetic properties at high temperatures. Another important characteristic is its ability to form alloys with a lot of different metals (BGS, 2009a). According to this property cobalt is rarely used in its pure metal form, but mainly as an alloying metal (BGS, 2009a). That is the case with rechargeable batteries, which represent today` s main cobalt end-use and EEE sector. Batteries account for 25 % of the worldwide demand for cobalt (CDI, 2006).

Cobalt is used for all three main rechargeable battery technologies. Nickel-cadmium, nickel-metal hydride and lithium-ion batteries are further utilised for mobile computers, cell phones, camcorders etc. (CDI, 2006). Other applications in the field of EEE include connectors on integrated circuits in the form of high quality electrical contacts (BGS, 2009a). Like beryllium, cobalt is used as luminescent material in TV sets (Behrendt et al., 1998).

Gallium
Gallium has the longest liquid range of all metals, ranging from 29.8 °C (melting point) to a boiling point of about 2,204 °C (Vulcan, 2009a). Even in its solid form gallium is a quite soft metal, which can be cut by using a knife (ISI, 2009).

[58] New Technology, which facilitates more efficient electricity generation compared with standard thin film and other silicon photovoltaics. (Knudson, 2008, p. 13)

For EEE, Gallium is especially significant due to its good semiconductor and optoelectronic properties. That is the reason why in the US[59] 74 % of the present consumption of gallium is used in integrated circuits, especially in mobile phones and 25 % in optoelectronic devices, from which laser diodes and LED account for 22 % and photo detectors and solar cells for about 3 % (Jaskula, 2011a).

According to USGS, more than 99 % of gallium consumption included GaAs (gallium arsenide) or GaN (gallium nitride). While GaAs is used for the production of both main applications (integrated circuit and optoelectronic devices), GaN is primarily utilised for the manufacturing of LED and laser diodes (e.g. blue laser diodes used in Blu-ray disc devices (Vulcan, 2009; Jaskula, 2011a).

Germanium
Germanium is a semiconductor, formerly classified as a semimetal (ISI, 2009), which, like antimony and tellurium, shows properties of both metals and non-metals (Vulcan, 2009b). It is a relatively strong but brittle element that is resistant to atmospheric oxidation (Guberman, 2011).

Worldwide, germanium is mainly used in infrared optics (30 %), fibre optics (20 %), particularly as a component of glass in telecommunications, catalysts for PET (20 %) and according to its semiconductor and photoelectric conversion-efficiency characteristics (Vulcan, 2009) in electronics and solar applications (15 %) (Guberman, 2011).

In detail, germanium contributes to EEE as a substrate for the production of high-brightness LED that are part of cameras, flashlights, mobile phone display screens and televisions. In the form of silicon germanium (SiGe), it replaces partly GaAs in high-tech products (e.g. mobile phones) (Guberman, 2011), in which it is particularly used for integrated circuits that work at ultrahigh frequencies. Such IC are important components of mobile internet and personal navigation devices in smartphones, digital cameras and laptops (Vulcan, 2009b).

Furthermore, germanium is used as a substrate for manufacturing solar cells for satellites and earth-based solar arrays (Guberman, 2011).

Gold
Gold is a lustrous, precious, heavy and chemically stable metal (Eurometaux, 2011), whose main properties include high resistance to oxidation and corrosion and high thermal and electrical conductivity (Chancerel, 2009).

Owing to its appearance and high price, gold is predominantly utilised for jewellery and arts, accounting for 69 % of the estimated end use in 2009. However, due to its conductivity, 9 % of the gold was used for electrical and electronics applications (George, 2011). Out of this, mobile phones and desktop personal computers amounted to almost 40 %, and large high-grade equipment like laptops and DVD players to another 29 % of gold present in small WEEE (Chancerel, 2009).

In electrical devices, gold is especially used in printed circuit boards (Eurometaux 2011) and mainly for the semiconductor industry as germanium-gold alloy to evaporate contacts (ISI 2009). In this connection, it is utilised for connectors, switch and relay contacts, soldered joints, connecting wires and connection strips (Geology). It is furthermore used for recordable compact discs, hybrid integrated circuits, resistors (Eurometaux 2011) and bonding wire (UNEP/Öko-Institut 2009).

[59] Due to a lack of European and worldwide data, information from USGS Mineral Yearbook 2009 is used to give an insight into main applications of Gallium.

Indium
Similar to gallium, indium is a very soft metal that combines a relatively low melting point (156.6 °C) with a high boiling point of 2080 °C. In alloys, even small quantities of indium improve hardness and corrosion resistance of the metals (ISI, 2009).

The majority of the worldwide end use of indium can be related to the EEE sector. This includes indium tin oxide (ITO) for thin-film coatings (84 %), mainly used for electrically conductive purposes in flat panel devices and, with a smaller share of 5 %, for electrical components and semiconductors (Tolcin, 2008).

ITO thin films that are both electrically conductive and optically transparent are especially utilised for the production of LCD, being an important component of flat screen TV, cell phones, computers and other electronic equipment (Vulcan, 2009c). Further uses include indium containing solders that prevent the leaching of gold components in electronic devices (Tolcin, 2011), photovoltaics that represented only a small share of indium's end use in 2007, but are expected to increase in the years to come (ISI, 2009), and indium-based LED, mainly utilised for the optical transmission of data and to a lesser extent for LED displays (Tolcin, 2011).

Lithium
Lithium is a very light and soft alkali metal that shows the lowest density of all solid elements and a low melting point of 180 ˚C (Jackson, 2007). Besides other unique characteristics, Lithium` s electrochemical reactivity facilitates its use in a great quantity of commercial products (Jaskula, 2011b).

For the EEE sector, batteries, predominantly in the form of Li-ion, Li-polymer and Li-metal (Behrendt et al., 2007), are the most relevant usage of Lithium, accounting for 23 % of lithium's global end use. Rechargeable lithium-based batteries particularly power portable electronic devices such as mobile phones and laptops (Jaskula, 2011b). In addition, non-rechargeable batteries are used in calculators, cameras, computers and watches (Jaskula, 2011c).

Lithium niobate is used extensively in telecommunication products such as mobile phones and optical modulators for components such as resonance crystals.

Palladium
Although the chemical properties of the different platinum group metals, covering platinum, palladium, iridium, osmium, rhodium and ruthenium, are very similar, their physical characteristics show considerable differences (BGS, 2009b).

For palladium, the most relevant properties are its high temperature stability, electrical conductivity and corrosion resistance (IPA, 2011). Furthermore, it is soft, ductile as well as the least dense of all PGM (BGS 2009b). It has a high melting point (1554 ˚C) compared to other metals, but the lowest of the platinum group metals (IPA, 2011).

Due to its specific properties, palladium is mainly used for the production of auto catalysts (45 %), but approximately 19 % of palladium` s global end use in 2009 was utilised for the electronics industry (Loferski 2011). This includes usage in broadcasting equipment, mobile phones, computers and electronic lighting (IPA, 2011).

In the EEE sector, palladium is predominantly utilised, according to its characteristics, for multi-layer ceramic capacitors (MLCC) (BGS, 2009b) that are widespread in electronic circuitry (Loferski, 2011). Aside from that, a smaller proportion of palladium is used in

hybrid integrated circuits (HIC), plating of connectors (BGS, 2009b), resistors (Johnson Matthey, 2007) and coating of MLCC and electrodes (IPA, 2011). In future, palladium is additionally expected to be an important element in the fuel cell sector, focusing on the powering of cars, houses and portable electrical equipment, such as laptops and mobile phones (BGS, 2009b).

Ruthenium
Ruthenium, as one of the platinum group metals, is hard, brittle, has a high melting point (2310 ˚C) and is therefore extremely difficult to work (BGS, 2009b), but in alloys it improves hardness and resistance to abrasion (IPA, 2011).

Almost 60 % of the ruthenium global consumption was used in electrical devices (Loferski, 2011), mainly utilised for computers and other EEE products such as digital TV recorders, home data centres and TV sets (IPA, 2011)..

In the EEE sector, ruthenium's main applications contain resistors and hard disk drives (perpendicular magnetic recording, PMR), where it is used to increase the density of data storage (IPA, 2011). Furthermore, small amounts of ruthenium are used in dye-sensitized solar cells, utilised as electron donating dye (ISI, 2009), and in the manufacturing of flat plasma display screens (BGS, 2009b).

Silver
Silver is one of the eight precious metals, has the highest electrical and thermal conductivity of all metals, is highly photosensitive, chemically inert to oxygen (EC, 2010a), has the highest degree of optical reflectivity and is more ductile and malleable than any other element except gold (Silver Users Association, 2010).

Almost half of silver's global demand (excluding investments) was utilised for industrial applications (The Silver Institute, 2010), especially for electrical and electronics components (Brooks, 2011) that can be found in microwave ovens, dishwashers, washing machines, refrigerators, air-conditioning, computers, mobile phones and TV sets (The Silver Institute, 2011).

On a component level, silver is particularly used in conductors, contacts, fuses, timers, conductive adhesives, switches (predominantly membrane switch panels) (Brooks, 2011), for circuit breakers, brazes and solders (The Silver Institute, 2011) and as silver-palladium in multilayer ceramic capacitors. Concerning specific product groups, silver is used in plasma flat screen display panels, silver-backed solar mirrors, thick-film and thin-film photovoltaic cells (Brooks, 2011), silver oxide-zinc batteries mainly used in cameras, watches and calculators (The Silver Institute, 2011), as coating material for CD and DVD, and for radio-frequency identification devices (RFID) in passports (Brooks, 2011).

Tantalum
Tantalum is a very hard, heavy metal (Vulcan 2009) that combines unique properties such as superconductivity, corrosion resistance, very high melting temperatures (2 996 °C), shape memory characteristics and a high coefficient of capacitance (BGS, 2011a).
The electronics industry accounts for approximately half of the worldwide end use of tantalum, mainly for the production of capacitors and circuit board connectors (Global Advanced Metals, 2010). Capacitors, in which it is used as a powder, are part of mobile phones, laptops, digital cameras, DVD players, flat screen TV and games consoles (Tanb, 2011).

Other major uses of tantalum include alloys, compounds, fabricated forms and ingots (Papp, 2011). As lithium tantalite, it is utilised for the production of surface acoustic wave

filters (mobile phones, hi-fi stereos and TV), in the form of tantalum oxide for the manufacturing of lenses in digital cameras and mobile phones, and in the form of tantalum ingot for computer hard drive discs (Tanb, 2011). In addition, tantalum nitride, a semi-conductor, is used in different electronic applications such as LED, solar cells, transistors and digital circuits (BGS, 2011a).

Tellurium
Tellurium shows properties of metals and non-metals (ISI, 2009). It is brittle, not very hard, poor in thermal conductivity, fair in electric conductivity and mainly combines with other metals to form tellurides (Encyclopedia Britannica, 2011).

According to USGS, tellurium is mainly used as a metallurgical alloying element in steel, copper, lead and iron and only in the second instance utilised for electronics applications (George, 2010). Other sources indicate both usages of tellurium to be equally important (each 40 %) when electronics and photovoltaics are grouped (UNEP/Öko-Institute, 2009).

Major electronics applications include thermal imaging, phase-change memory and photoelectric devices, where tellurium is particularly used in high-purity (George, 2010), Blu-ray Discs and solar cells (Vulcan, 2009e). In the form of the semiconducting bismuth telluride, it is used in thermoelectric coolers, utilised for integrated circuits and laser diodes (George, 2010) and as cadmium telluride in thin film photovoltaics (EC, 2010a).

Tungsten
Tungsten is one of the heaviest metals with a density comparable to gold (BGS, 2011b). Furthermore, it has the second highest melting point of all elements (3422 ˚C), excellent high temperature mechanical properties, and an extremely low vapour pressure (ITIA, 2005); the lowest coefficient of expansion of all pure metals, and shows high thermal and electrical conductivity (BGS, 2011b).

In 2008, tungsten mill products accounted for 8 % of its European end use (ITIA 2005), including pure metal products and alloys, utilised for lighting filaments, electrical and electronic contacts, electrodes and wires (Shedd, 2011). In electrical and electronic devices, most of tungsten is used in light bulbs, TVs and magnetrons for microwave ovens (ITIA, 2005). Other EEE relevant uses involve chemical applications (approximately 11 % of European use) utilised for the production of semiconductor circuits and circuit boards (BGS, 2011b).

Furthermore, tungsten is used for electron emitters, cathode ray tubes (TV sets and computer displays), electron tubes, as tungsten disks for high power semiconductor devices, as tungsten charger wires (photocopiers, laser printers, air cleaners), in form of tungsten-copper alloy for heat sinks, as molybdenum-tungsten alloy targets for LCD panels (ITIA, 2005), and as nickel-tungsten alloy for connectors in portable electronics (BGS, 2011b).

Rare Earth Elements
Rare Earth Elements (REE) are used in different fields of EEE, e.g. in liquid-crystal displays or plasma displays, in speakers or in nickel-metal hydride (NiMH) batteries (which are used in some portable devices, but mainly in electric vehicles). The most relevant single application are neodymium-magnets in electronic components with hard disks. According to the Japanese company Shin-Etsu (Oakdene Hollins, 2011) around one-third of the neodymium-magnets that cover about 20 % of the total demand for rare earth elements, are used in hard disk devices. It is estimated that around 1,700 t neodymium (corresponds to 2,150 t neodymium oxide) were embedded in hard disks in PC including laptops which

were sold in 2008 (cf. Öko-Institute, 2011). Neodymium together with dysprosium, terbium, yttrium and europium can be regarded as the five REE with the highest criticality in terms of the importance to clean energy production. Nevertheless, EEE applications do not seem to be one of the main drivers for future supply risks. Especially for hard disks, substitution by new technologies like solid-state disks (SSD) with lower contents of REE can be expected.

Annex II: Methods used in the identified Japanese materials to measure the metal content

A. MOE & METI (Ministry of the Environment and Ministry of Economy, Trade and Industry). 2010. Reference 3. Result of the Study of Metal content of Small Home Electrical Home Appliances.

In this study, measurement of the metal content of specific components of a product (e.g. LCD, printed circuit board) as well as that of the overall product was conducted. The sample materials are prepared as follows.

1. Manual dismantling of sample products into components that are to be measured.
2. Breaking the components into small pieces of less than 5 cm.
3. Further cut the pieces with the cutting mill into pieces sized less than 2 mm.
4. Repeat the mixture and extraction of sample materials and obtain a sample of 100-200 g.
5. Further crush the sample materials into less than 0.2 mm with freeze cutting machine.

The crushed sample materials were then analysed via ICP (inductively-coupled plasma optical) emission spectrometry or atomic absorption spectroscopy analysis.

The parts that cannot be broken down went through X-ray fluorescence analysis.
(Page 27-28 of the material by MoE & METI, to which the result was appended as Reference 3)

B. JOGMEC (Japan Oil, Gas and Metals National Corporation). 2008. Working Paper on the Development of Efficient Recovery Systems of Less Common Metals. 2007. (in Japanese)

The study concentrated on the analysis of printed circuit board. The materials in the sample products were prepared for analysis as follows:

1. Manual dismantling of sample products to take out printed circuit board.
2. Cut the board into 5 cm square with metal-cutting scissors.
3. Further crush the square into 0.5 mm with the cutting mill (parts that are too thick to be crushed are taken out).

The crushed sample materials went through X-ray fluorescence analysis, followed by the chemical analysis indicated below.

- Au, Ag, Pd. Pt: mat melting→ ICP emission spectrometry.
- Al, Fe, Cu, Zn, Sn, Ba, Pb: digestion in alkaline solution hydrochloric acid → ICP emission spectrometry.
- AS, Se: digestion in hydrochloric acid → Frameless atomic absorption spectroscopy analysis.
- Br: combustion →ion chromatography.
- Hg: redox heating → atomic absorption spectroscopy analysis.

- Other elements → digestion in alkaline solution hydrochloric acid → ICP emission spectrometry.

The study acknowledges various limitations related to X-ray fluorescence analysis compared to the chemical analysis (page 46-47).

C. Kida, Akiko, Shirahase, Tomoko and Kawaguchi, Mitsuo. 2009. Metal Contents including precious metals in waste personal computers. Material Cycles and Waste Management Research 20 (2), 59-69 (in Japanese).

The study utilized the so-called "compiling method", which consisted of the following steps:

1. Dismantling of a PC to the extent that it consists of one composite material.
2. Develop sample from each composite material and analyse the elements in the material via chemical analysis.
3. Add up the element composition of each composite material.

For the printed circuit board, the results based on the compiling method was compared with those using ICP emission spectrometry and ICP mass spectrometry, as well as all metal analysis via mass combustion (page 60).

D. Chuo Kankyo Shingkikai (Central Council on the Environment). 2011. Material 2 "About the Ways of Organising Recycing Systems for Small Electrical Home Appliances." Appendix to Reference 1. Content of useful metals in Small Home Electrical Home Appliances (circuit board, components, break-down of materials).

This publication discusses how they estimated the number of products that would be discarded per year. Regarding the content of the metals in respective products, however, they rely on other studies, such as Study A.

E. Oguchi, Masahiro, Murakami, Shinsuke, Sakanakura, Hirofumi, Kida, Akiko and Kameya, Takashi. 2011. A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. Waste Management. 31 (2011) 2150-2160.

This work is in English and you can find information on page 2152. Following is the excerpt of methods used for the analysis.

"For our measurements, 62 end-of-life products categorized into 12 equipment types were dismantled and separated into materials. Each material was then weighed, and the weight fraction was calculated.

Metal content was measured for some of the dismantled printed circuit boards, which are made of composite materials containing various kinds of metals, using an analytical procedure proposed for the determination of a wide variety of metals in composite materials. The procedure is a modification of IEC 62321, the determination procedure for regulated metals in the Restriction of Hazardous Substances Directive (RoHS) directive (IEC, 2008). Printed circuit boards were cut and ground into small particles (preferably to a particle size of <0.25 mm) and digested with aqua regia, alkaline solution, or hydrochloric acid. The metal concentration was then determined using inductively-coupled plasma optical emission spectrometry (ICP-OES) and mass spectrometry (ICP-MS)."

F. Oguchi, Masahiro. 2007. Study on analysis of lifespan distribution and product-based material flow of electrical and electronic products. Ph.D. Thesis. Yokohama National University (in Japanese with English figures and tables).

For CRT TV and desktop PC, the parts evaluated were first dismantled, which were crushed into pieces of less than 5 mm. After being well mixed, 2-20 g is taken as samples. The parts that include plastics, such as printed circuit board and cover, are combusted in the electrical oven with 800 degrees Celsius. The samples or the combustion residues were digested with heat adding aqua regia, and analysed using inductively-coupled plasma optical emission spectrometry (ICP-OES). The gas emitted from the electrical oven is collected with filtration paper and the paper, after being digested with acid, was also analysed in the same way. The elements analysed include: Ag, Al, As, Au, Bas, Be, Bi, Cd, Co. Cr, Cu, Fe, Ga, Ge, In, Li, Mn, Ni, Pb, Pd, Pi, Rh, Sb, Se, Sn, Sr, Ta, Te, Ti, Tl, V, W, Zn and Zr.

For the batteries, end-of-life batteries are manually dismantled into their main materials. Aqua regia was added to each material and was digested with heat. After filtrating substances that could not be melted, each material was analysed using inductively-coupled plasma optical emission spectrometry (ICP-OES). The elements were added up taking into consideration the amount of elements found in each material and the weight of the respective materials (page 158-159).

Annex III - Collected WEEE in the EU in 2007 and 2008

Table 39 shows the different product categories the collection in the WEEE Directive (EU-Commission, 2002) put on the market 2007 and 2008, of WEEE and the treated WEEE.

Table 39 -EEE put on the market and WEEE collected and treated in EU-27 in 2007 and 2008.

WEEE category		EU-27 2007	EU-27 2007	EU-27 2008	EU-27 2008
	Put on the market	Tonnes	% of put on the market	Tonnes	% of put on the market
1	Large household appliances	4,437,384	47.0	4,717,765	46.7
2	Small household appliances	789,616	8.4	834,877	8.3
3	IT & Telecommunication	1,450,214	15.4	1,487,839	14.7
4	Consumer equipment	1,034,860	11.0	1,204,181	11.9
5	Lighting equipment	619,670	6.6	574,803	5.7
5a	Gas discharge lamps	84,983	0.9	138,569	1.4
6	Electrical & electronic tools	531,732	5.6	643,965	6.4
7	Toys, leisure & sports equipment	264,658	2.8	242,242	2.4
8	Medical devices	73,543	0.8	102,448	1.0
9	Monitor & control instruments	75,892	0.8	75,208	0.7
10	Automatic dispensers	75,209	0.8	71,813	0.7
	Total put on the market	9,437,760		10,093,711	
	Total collected from private households and others	Tonnes	% of the total collected amount	Tonnes	% of the total collected amount
1	Large household appliances	1,221,517	54.92	1,747,737	56.2
2	Small household appliances	125,086	5.62	180,184	5.8
3	IT & Telecommunication	390,291	17.55	575,976	18.5
4	Consumer equipment	343,285	15.43	442,746	14.2
5	Lighting equipment	29,950	1.35	32,038	1.0
5a	Gas discharge lamps	24,482	1.10	34,664	1.1
6	Electrical & electronic tools	33,789	1.52	54,283	1.7
7	Toys, leisure & sports equipment	11,177	0.50	15,413	0.5
8	Medical devices	26,813	1.21	7,428	0.2
9	Monitor & control instruments	7,431	0.33	6,388	0.2
10	Automatic dispensers	10,544	0.47	15,200	0.5
	Total collected from private households and others	2,224,366		3,112,059	
	Total treated	Tonnes	% of the collected amount	Tonnes	% of the collected amount
1	Large household appliances	1,155,081	94.6	1,351,370	77.3
2	Small household appliances	124,628	99.6	170,023	94.4
3	IT & Telecommunication	348,977	89.4	445,985	77.4
4	Consumer equipment	405,061	118.0	491,691	111.1
5	Lighting equipment	16,094	53.7	19,030	59.4
5a	Gas discharge lamps	20,568	84.0	27,511	79.4
6	Electrical & electronic tools	26,656	78.9	40,191	74.0
7	Toys, leisure & sports equipment	10,574	94.6	14,424	93.6
8	Medical devices	25,773	96.1	6,475	87.2
9	Monitor & control instruments	7,997	107.6	6,282	98.3
10	Automatic dispensers	8,609	81.6	11,877	78.1
	Total treated in Member States and outside the EU	2,150,019	96.7	2,584,860	83.1

Source: Own calculation based on (Eurostat, 2011). There is no reporting for Malta and Slovenia

Annex IV: Composition of PV modules

Table 40: Composition of PV modules (framed, except for CdTe modules) (Sander 2009)

Technology	fraction	Share [%]
c-Si	glass	63
	Al	19
	Si	4
	Cu (cable)	0,6
	Organics	1,1
	Ag	<0,01
	Sn	<0,1
	Pb	<0,1
a-Si	glass	86
	Al	12
	Si	<0,1
	Organics	2
	Sn	<0,1
	Pb	<0,1
CdTe	Glass	95,4
	Al	<0,01
	Te	0,07
	Cd	0,07
	Cu (cable)	0,9
	Ag	<0,01
	organics	3,5
	Sn	<0,01
	Pb	<0,01
CIS	Glass	80
	Al	12
	In	<0,02
	Ga	<0,01
	Se	<0,03
	Cu (cable)	0,85
	Organics	6
	Sn	0,12
	Pb	<0,1