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Sustainable Materials Management

RAW MATERIALS SAVINGS BY URBAN MINING: THE CASE OF DESKTOP AND LAPTOP COMPUTERS IN BELGIUM

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List of Abbreviations

ABS Acrylonitrile Butadiene Styrene

ABS/PC Acrylonitrile Butadiene Styrene/Polycarbonate

CEENE Cumulative Exergy Extraction from the Natural Environment

CRT Cathode Ray Tube

EEE Electrical and Electronic Equipment

EU European Union

FPD Flat Panel Display

LCA Life Cycle Assessment

MFA Material Flow Analysis

MWR Material Weight Recycling

OVE Other appliances

PC Personal Computer

PCB Printed Circuit Board

PE Polyethylene

PGM Platinum Group Metal

POM Put On the Market

PMMA Poly(Methyl Methacrylate)

PP Polypropylene

PS Polystyrene

RMC Recycled Material Criticality

REE Rare Earth Element

WEEE Waste Electrical and Electronic Equipment

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1 Introduction

1.1 General

Waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams, in amounts as well as in importance. The use of electrical and electronic equipment (EEE) has grown rapidly in recent decades, as a result of ongoing technological innovations, leading to decreasing lifespans and a continuous increase in consumer demand. This in turn gives rise to increasing WEEE quantities being disposed of by the users (Wang et al., 2013; Widmer et al., 2005).

WEEE is a very complex and non-homogenous waste stream. Base metals like iron and aluminium, together with plastics, often perform a structural function, and are therefore present in large quantities (Townsend, 2011). Other elements on the other hand, such as precious metals and rare earth elements (REEs), are present in much smaller amounts, and are incorporated in the product due to their extraordinary and sometimes exclusive properties, which are essential for the proper functioning of the device (Hagelüken, 2012).

The large complexity and diversity in types of devices, and even within one type of device, means that nearly every element in the periodic table can be encountered in WEEE. Some are potentially hazardous, such as lead, mercury or cadmium, while others have a large value and are therefore important to recover, like gold, silver or platinum (Townsend, 2011). Recycling of WEEE thus has a twofold purpose. It must be seen as a dangerous waste stream, which, if not treated properly, can cause severe environmental and human health damage (Tsydenova and Bengtsson, 2011). On the other hand, the many materials that constitute WEEE form an enormous resource potential. Printed circuit boards (PCBs) for example can contain more than ten times the concentration of precious metals, compared to the respective metal ores (Betts, 2008). The sustainable management of this waste stream is thus important to prevent the loss of these materials and to mitigate the growing shortage of resources (Hagelüken and Meskers, 2008).

The European Commission recognizes this, as they defined waste as one of the key resources to lower the dependence on imports of raw materials (European Commission, 2011). Indeed, raw material resources are crucial for the economy, but very little primary production occurs within the member states. Thus, as their availability is coming increasingly under pressure, an assessment of the criticality of various raw materials was made. The criticality of a material consists out of two aspects, that is the economic importance, combined with the supply risk. The latter can be the result of for example political-economic instability in the producing countries, or the concentration of supply in a limited number of nations. The result of this assessment is shown in Figure 1 (European Commission, 2014).

Many of the materials deemed critical by the ad-hoc working group, which performed the assessment, are present in electronic equipment, especially in high-grade appliances such as IT devices. Examples are REEs used in permanent magnets in hard disks (Binnemans et al., 2013), indium in flat screens (Blaser et al., 2012) and platinum group metals (PGMs) on PCBs (Cui and Zhang, 2008). These devices could thus form a valuable stream for the recovery of these resources.

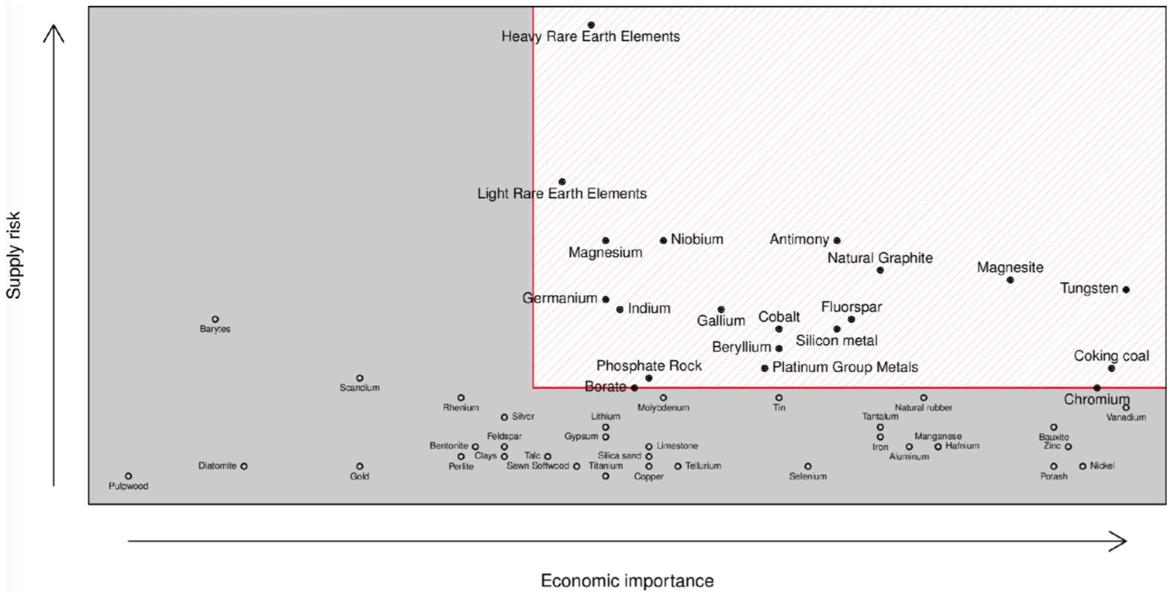


Figure 1: Results of the criticality assessment. The raw materials deemed critical are shown in the red shaded area (European Commission, 2014).

1.2 Electronic Waste Recycling

Clearly, the wasted appliances need to be collected and treated properly for this recovery of resources to succeed. This is achieved trough the WEEE recycling chain, which generally comprises three major steps (see Figure 2). First of all, the discarded devices are collected and sorted. Their functioning is checked, and the device is refurbished and reused, if appropriate.

The non-functioning part of the waste stream is then sent to a primary treatment facility, where the devices are dismantled and processed mechanically. The main objective here is the separation of the different materials present in the waste stream, to be able to further treat them separately. This is achieved firstly through manual dismantling, where certain components are removed to take out hazardous elements (e.g. asbestos or mercury containing parts), or to recover highly valuable and high-grade materials (e.g. PCBs and cables). Thereafter, the remaining waste stream is usually shredded, to allow for liberation of the different materials, which are subsequently separated from each other through a combination of mechanical separation steps, which rely on differences in physical properties of the various materials, such as magnetism, density or electrical conductivity (Cui and Forssberg, 2003).

As a final step, the different materials are sent to an end-processing facility, where they are processed into secondary raw materials. This includes among others metal smelters, where for example iron and steel scrap are processed into secondary steel, and plastics recycling plants, where secondary plastics are produced. Another option for organic materials is incineration, with which heat and electricity can be provided.

The total efficiency of this recycling chain depends on the efficiency of the different waste valorization steps. Often, the collection step is the bottleneck in the chain (Bernstad et al., 2011). Part of the WEEE stream still does not reach the appropriate channel for proper waste treatment, for instance because it is disposed in normal household waste (Darby and Obara,

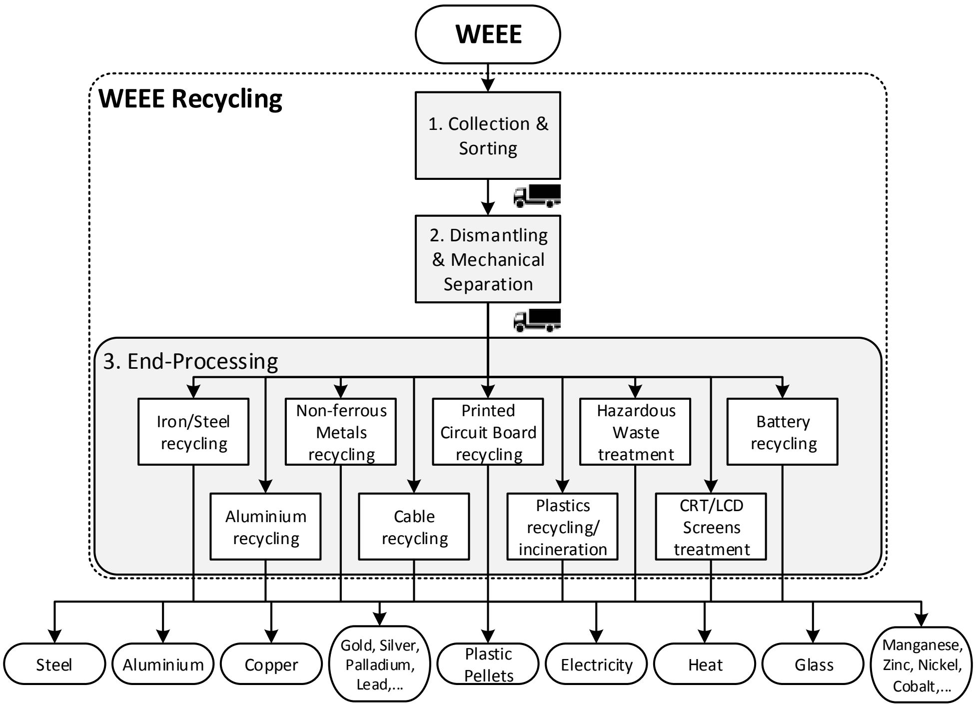


Figure 2: Overview of the general WEEE recycling steps.

2005), or kept in stock by consumers who expect these appliances to still have some value (Kang and Schoenung, 2005). Finally, also large illegal exports to regions without appropriate legislation prevent proper collection and treatment (Hagelüken and Meskers, 2008).

This illegal export is especially important for IT devices, as they are small and easily transportable, and because of the high value (reuse or material) of their components (such as PCBs). This is often done under the label of 'second hand goods', although their functioning can be questionable. Upon arrival, in usually developing countries, much of the equipment never makes it to the second hand market, but is dismantled to extract the raw materials, often in poor circumstances. Even if the appliances still function and are reused, they will become waste sooner or later and be disposed of locally. These sub-optimal recycling operations can cause the toxic components to be released, being harmful to the environment and human health (Bisschop, 2012).

To improve the collection and subsequently the recycling of WEEE, the European Union (EU) adopted the WEEE Directive (European Parliament and Council, 2012). Here, collection targets are defined, and starting in 2016, these will no longer be defined as a fixed amount per inhabitant (currently 4 kg/inh), but as at least 45 % of the average amount of EEE put on the market (POM) in the three preceding years. From 2019 onwards, this will increase to at least 65 % of EEE, or alternatively 85 % of WEEE produced. Besides that, the directive also subdivides the WEEE in different categories, and defines recycling and recovery targets for each of the categories of WEEE collected, based on mass.

The choice of the directive for a focus on mass, means that the recyclers can concentrate on the materials which are present in large amounts in the waste stream, such as iron or plastics, to achieve the imposed targets. In this situation, materials existing in small quantities, like precious metals, can potentially be neglected, although their primary production causes large environmental impacts. The recycling of these materials could therefore achieve a large avoided burden per unit of mass. It is consequently suggested to base the targets not on overall mass, but on the recycling of individual materials, to improve the benefits achieved through recycling (Bigum et al., 2012; Huisman et al., 2008).

However, to achieve this, detailed composition data of EEE is needed. This proves to be difficult, because of the large complexity and variety of the appliances. Additionally, producers are reluctant to provide detailed information on their products. This makes data gathering a difficult task. Therefore, there is a need for detailed quantity and composition analyses to be performed, to enhance the accuracy of assessments of the recycling of WEEE. Similarly, data on the generation of WEEE is not readily available, which is crucial for reporting the achieved collection targets set by the EU. Efforts thus have to be made to resolve this insufficient data availability.

2 Objectives

As mentioned in Section 1.2, it is suggested that collection and treatment targets should be based on the recycling of individual materials, rather than on overall mass. This calls for detailed data to be collected on two levels. On the micro-level, material composition data for all components of the WEEE should be established. With this information, the treatment of the waste stream can be analyzed, and the treatment results quantified. This can subsequently be combined with data on the macro-level, expressing the amount of WEEE that is generated and collected in Belgium. The resource potential of the waste stream can thus be determined. The reference year for this study is 2013.

Apart from mass targets, the potential environmental benefit achieved through the recycling of WEEE is assessed as well. This is performed by comparing the recycling chain with a second scenario, in which the appliances are not collected properly and are landfilled after use. In this scenario, all materials and services (e.g. electricity) produced through the recycling operations need to be supplied through the primary production chain.

As IT equipment is especially rich in valuable and critical materials (see Section 1.1), the recycling of a desktop and a laptop computer is selected as a case. This desktop computer also includes the peripheral equipment, namely a keyboard, mouse and screen. For the laptop, no peripheral equipment is considered.

To achieve these objectives, the two first stages of the recycling chain, first the collection and sorting, and second the dismantling and mechanical separation (which form the primary treatment), are inventoried on the micro-level, to establish information on the treatment processes. This includes constructing a material flow analysis to examine the material flows through the treatment process. Furthermore, the utilities required are registered, such as energy, chemicals and transport. The final step of the recycling chain, which is the end-processing, as well as the complete landfill scenario, are modeled using the Ecoinvent database.

To assess the performance of the recycling chain, three analyses will be carried out. A first indicator will be calculated, quantifying the effectively recycled weights of target materials, while a second indicator expresses the recycling efficiency of critical raw materials through the recycling process. Finally, the environmental impacts of the two waste treatment scenarios are determined, and will be expressed in cumulative exergy extraction from the natural environment (CEENE), to quantify the natural resource consumption.

As mentioned in Section 1.2, the collection step is a major bottleneck in the functioning of the WEEE recycling chain. A market analysis will therefore be made to assess the collection efficiency for laptops. This is accomplished through a model describing the waste generation, starting from the amount put on the market in the preceding years. This can then be compared to the amount which is collected and sent to proper treatment.

3 Materials and Methods

As mentioned in Section 1.2, the first step in the WEEE recycling chain is the collection and sorting. Then, the collected waste stream is dismantled and separated mechanically, to be able to further process the different materials. Information on the first step was collected in cooperation with Recupel, which organizes the collection in Belgium. For the second step, the partner was the Galloo recycling company in Menen, Belgium. Here, several company visits with guided tours, meetings and e-mail communication ensured that extensive knowledge on the treatment process was built up.

3.1 Description of the Recycling Processes

3.1.1 Collection and Sorting

Recupel is a producer responsibility organization, which organizes the collection and treatment of WEEE in Belgium, for those manufacturers and importers who joined this scheme. Collected WEEE is first checked, and equipment that still can be used is repaired, refurbished or cleaned. The rest is divided into five fractions: Cooling and freezing appliances, Big white goods, Television screens and monitors, Gas discharge lamps, and Other appliances (OVE). IT equipment is part of the OVE fraction (Huisman and Baldé, 2013; Verberckmoes, 2014). Recupel then arranges the transport of the waste stream to an appropriate treatment facility.

Unfortunately, Recupel was not able to provide the distance covered by the collection transport. An estimation thus has to be made. For the case of Switzerland, Wäger et al. (2011) mention an average collection distance for WEEE of 40 km. Although Switzerland is a bit bigger than Belgium, in this study a conservative average collection distance of 60 km is estimated, consisting for 15 % of light-duty transport, and for 85 % of heavy-duty transport.

3.1.2 Dismantling and Mechanical Separation

As mentioned before, in this study, the treatment process of computers and peripherals at Galloo (see Figure 3) is further analyzed, which is a very relevant case for Belgium, as almost half of the OVE fraction collected in Belgium is treated here.

Here, the PC towers and laptops are manually dismantled, to take out the various components that undergo different treatments. Some parts are sent straight to an end-processing facility, such as the batteries and the PCBs. Other components on the other hand are treated further in-house to additionally separate the materials they are made of. These further treatment operations include shredding and the use of among others magnets and eddy current separators. Some components are also joined with the main OVE fraction, the processing of which is described further on.

The CRT screens are dismantled manually as well, and the various resulting fractions are mainly further processed, similarly as mentioned for the desktops and laptops. The FPD screens and dismantled laptop screens are shredded in a special shredder, which ensures that no harmful compounds are released. The resulting material is thereafter treated further in the normal post-shredder treatment, plastics and flotation lines of the OVE processing (see further). The two different mouse types and the keyboard are treated directly with the OVE stream.

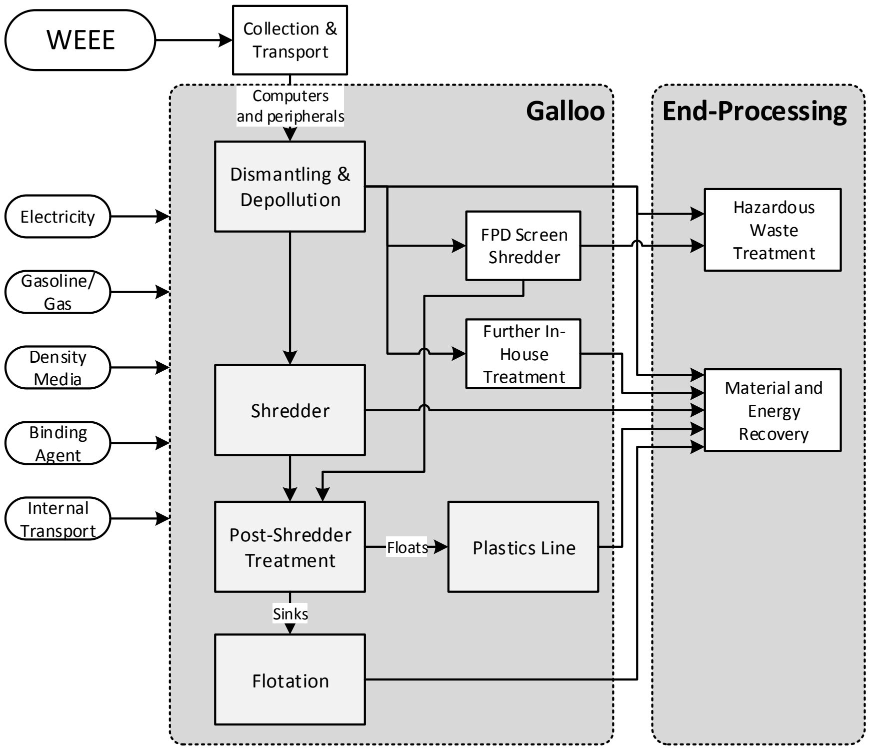


Figure 3: Simplified scheme of the treatment process of computers and peripherals at Galloo. In reality, about 25 different output streams are defined for the analysis.

The treatment of the OVE fraction takes place in four large main treatment units. First of all, the waste stream is sent to the big shredder, where the material is comminuted, and magnets take out a large iron and steel fraction. Hereafter, the remaining stream goes to the post-shredder treatment line, where the main aim is to separate the waste material in a light (mainly organics) and a heavy (mainly metals) fraction, using density-based methods. The light fraction is further treated in the plastics line, where mainly further density and infrared separation make sure that a clean recyclable plastics fraction is obtained. Besides that, a high quality fuel is separated, which can be used in incineration plants to produce heat and electricity. The final main treatment unit is the flotation line, where the sinks from the post-shredder treatment are processed. Here, additional density separation is combined with among others magnets and eddy current separators, to isolate the various metals in the remaining waste stream as much as possible.

To carry out the separation of the materials, utilities are needed. The main utility used is electricity to power the machines. This electricity is provided by a digestion plant, which treats mostly agricultural waste to produce biogas. Furthermore, various density media are added to water to accomplish a desired density value. The water used for the separation is internally recycled, and losses are compensated with rainwater that falls on site, so no net intake of water is required. Additionally, a chemical additive is used as a binding agent to capture mercury released during the shredding of FPD screens. Also, a small amount of gasoline is used in a drying module in the flotation treatment unit. Here, usually recycled gasoline from waste cars is used, if available. Alternatively, natural gas from the grid is burned. Finally, the internal transport between the different sites of the company is considered as well. The use of all these utilities is taken into account in the impact assessment for the recycling operations at Galloo (Waignein, 2014).

3.1.3 End-Processing

The end-processing is carried out to produce secondary raw materials from the fractions that leave the separation plant. The following end-processing operations are considered:

- Iron and steel scrap is sent to a steel manufacturing plant in Luxembourg, where an electric arc furnace is used to produce secondary steel. It is assumed in this study that low- or un-alloyed steel is made.
- Aluminium scrap is remelted to secondary aluminium in an aluminium smelter. This is carried out in Italy for almost all secondary aluminium, while the rest is processed in China.
- Secondary magnesium is produced from magnesium scrap in a German magnesium smelter.
- A copper smelter treats the copper scrap to produce secondary copper, almost all of which is produced in Belgium, and a small part in China.
- A Belgian integrated smelter processes fractions rich in non-ferrous metals, such as PCBs. A number of metals is recycled here, namely copper, silver, gold, palladium, lead, nickel, antimony, tin, and bismuth.
- The separated plastics polymers polypropylene (PP), polystyrene (PS), polyethylene (PE), acrylonitrile butadiene styrene (ABS) and poly(methyl methacrylate) (PMMA) are recycled to secondary plastic pellets. The first four polymers are processed at the sister company of Galloo, Galloo Plastics, located just across the border in France, while PMMA is treated in China.
- Laptop batteries are sent to pyrometallurgical battery treatment in Belgium. According to Hischier et al. (2007), steel, cobalt, non-ferrous metals (for which copper is used as a proxy) and manganese oxide are recovered as secondary raw materials.
- Small button cell batteries from PCBs are collected and sent to the Belgian recycling scheme. Because of lack of information though, and because the mass is not significant, this stream is assumed to be landfilled.
- Non-recyclable plastics and other organic fractions are incinerated. The high quality fuel, separated in the plastics line (see Section 3.1.2), is sent to an incinerator in Sweden which produces electricity and district heating, while other organic streams are treated in a Belgian hazardous waste incinerator, where some energy recovery through electricity production is performed as well.
- Base metals, such as iron, which end up in a copper or integrated smelter as impurities, are transferred to the slag, which can be used as a cement, replacing regular portland cement (Kellenberger et al., 2007; Siddique and Khan, 2011). Similarly, organic impurities in smelters act as an additional reducing agent and fuel, thus replacing cokes (Schlüp et al., 2009).
- Mineral fractions recovered at Galloo, as well as inorganic fractions ending up in a smelter and which are transferred to the slag, are used as a construction material, thus replacing gravel from mines.

The transport activities from Galloo to the end-processing facility are taken into account as well. These are mainly performed using road transport, as well as ship transport to China for various metals and plastics, and to Sweden for the high quality organic fuel.

3.2 Scope

3.2.1 Functional Unit

A functional unit is defined to represent the function of the studied system and to allow a comparison between different systems (Ledón et al., 2012). In this study, the used functional unit is a unitary functional unit (reference flow, Laurent et al. (2014)), corresponding to the treatment of one tonne (1 000 kg) of desktop personal computers (PC) with peripherals. These peripherals include a mouse, keyboard and screen. For the mouse, it is estimated that in 75 % of the cases, an optical mouse is used, compared to a ball mouse. Similarly, also a ratio for the screen type is used, which is the amount of cathode ray tube (CRT) screens to flat panel display (FPD) screens treated at Galloo. It follows that in 87 % of the cases, a CRT screen is used, and in the others cases an FPD screen. Besides that, the treatment of one tonne laptop computers is also considered, with the assumption that no peripherals are used, so the power charger is neglected.

3.2.2 System Boundaries

The system boundaries are presented in Figure 4. In this study all recycling steps after the product is discarded by the user are included. It thus starts with the collection and sorting step, the subsequent dismantling and mechanical treatment step, and finally the end-processing step, where secondary materials and services (like electricity or heat) are produced. The first two steps are included in the foreground system, as data was gathered to model these operations. The final step, as well as the production processes of all the utilities used in the foreground system, are covered by the background system. The quantitative information for the background system was modeled using the Ecoinvent v.2.2 database (Ecoinvent Centre, 2010), with some modifications where necessary (see Section 3.4.3).

The recycling scenario is compared to the baseline scenario where the waste stream is completely landfilled. In this landfill scenario, primary production of the same materials and services as produced by the recycling process is necessary, to account for the primary production avoided due to the recycling process. These primary production processes, as well as the landfilling activity, are included in the system boundaries as part of the background system. The two scenarios are shown in Figure 4 as well.

It is assumed that the incoming waste carries none of the upstream burdens into the waste treatment system (referred to as the zero burden assumption), to be able to easily compare the two treatment scenarios (Ekvall et al., 2007).

3.3 Flow Analysis

3.3.1 Market Analysis

Quantitative information on the total amount of WEEE generated is usually unavailable. As the collection targets set by the EU will be based on the volume EEE put on the market, or WEEE

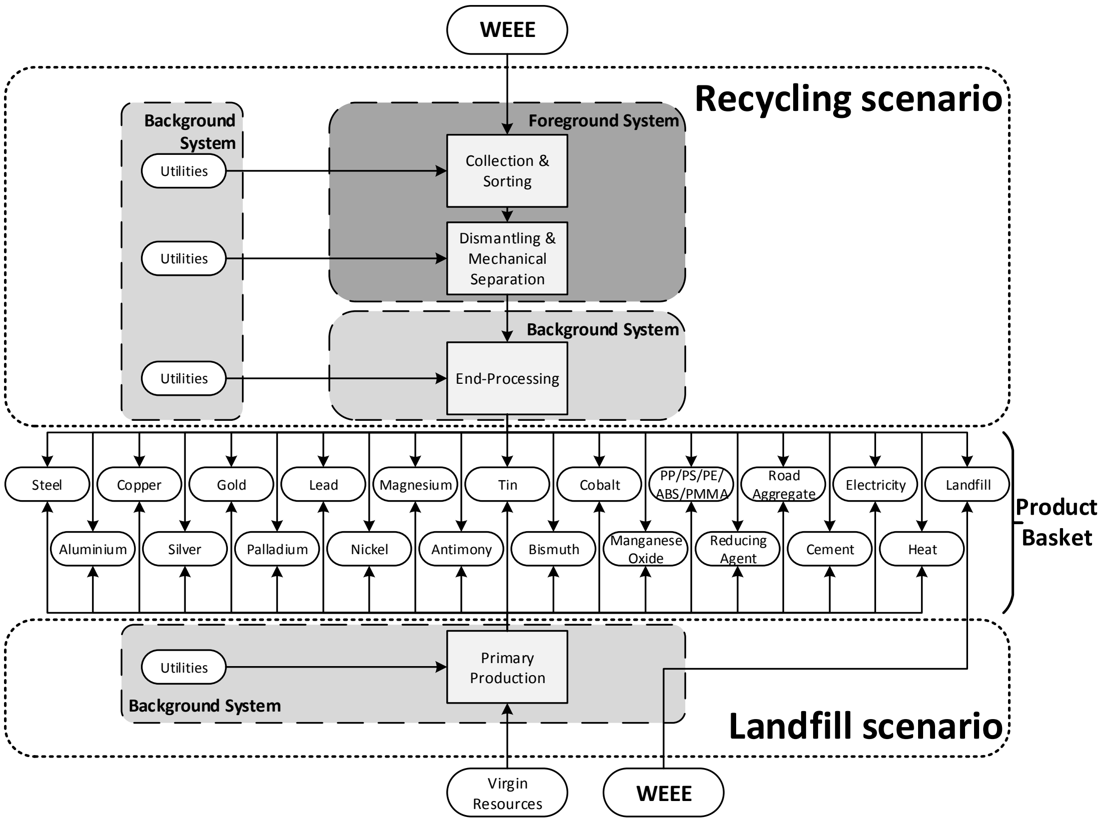


Figure 4: Schematic overview of the two scenarios for the treatment of computers considered, with the system boundaries of the foreground and background system.

generated (see Section 1.2), macro-level values on the production of WEEE need to be known. No established method exists for determining these volumes though (Huisman and Baldé, 2013).

One possible estimation technique, discussed by Wang et al. (2013), is used in this study. Here, input-output analysis is explained, which quantitatively describes the dynamics, magnitude and interconnection of three variables, namely product sales, stocks and lifespans. Commonly, two of these three variables are applied for computation, although the third variable can be used to increase the overall data-quality.

In this study, the volume product sales is first of all estimated. This is done using the Eurostat Europroms database, which is a combination of production (Prodcom) and international trade per country (Combined Nomenclature) statistics (Prodcom code desktop: 26.20.13.00; laptop: 26.20.11.00) (Eurostat, 2015). As the quality of the statistics for the desktops was deemed to be too low, only laptops will be analyzed further on.

Next, the lifespans of the product are used to estimate the lifetime of the product before it becomes waste. This discard-based lifespan profile is modeled using the Weibull distribution function, presented in Equation 1:

$$L^{(p)}(t,n) = \frac{\alpha(t)}{\beta(t)^{\alpha(t)}}(n-t)^{\alpha(t)-1}e^{-\left[\frac{(n-t)}{\beta(t)}\right]^{\alpha(t)}} \quad (1)$$

Here, $\alpha(t)$ is a shape parameter, while $\beta(t)$ is a scale parameter. As the lifespan of products changes through time, because of social and technical development, these parameters vary through time as well, and have to be modelled corresponding to each historical sales year. This distribution describes the probabilistic obsolescence rate in evaluation year n of the batch of products sold in historical year t, so the percentage of the products sold in year t which will become waste in year n.

Now, the product sales (POM) of historical years t, starting from the initial year t_0, can be multiplied with the lifespan profile of the respective year, to obtain the total waste generation of a product W in a specific evaluation year n:

$$W(n) = \sum_{t=t_0}^{n} POM(t) \cdot L^{(p)}(t,n) \tag{2}$$

This value can then be compared to the amount of waste collected through the recycling scheme, to assess the efficiency thereof.

3.3.2 Material Flow Analysis

A material flow analysis (MFA) studies the flux of materials through a studied system which is defined in space and time, through quantification of inputs and outputs. This can be done on a substance basis, tracking each element through the system (Bringezu and Moriguchi, 2002).

In order to determine the material flows trough the WEEE recycling chain on the micro-level, the dismantling and mechanical separation plant of Galloo was investigated. As mentioned in Section 3.1.2, the waste appliances are manually dismantled at Galloo into the different components, and the total mass of each dismantled component after the treatment of a large batch of waste computers (about 40 tonnes of desktop computers and 20 tonnes of laptops) was provided. For each manually separated component, a material composition from various literature and other sources, presented in Table 1, was used to establish the total input into the process. Components present in desktop as well as in laptop computers, such as hard disk drives, are assumed to have the same composition, due to lack of more specific data, and because they are further treated together. It was always attempted to use the most reliable, representative and detailed data available.

As a result of this, a large list of materials (or material categories) was obtained, presented in Table 2. Some of these contain multiple substances. The category Fe comprises all ferrous metals, while Cu contains copper as well as a small amount of brass. The plastics category is an aggregate for all plastics present in the waste stream, and the other organics class contains additional organic substances, such as rubbers or the liquid crystals from FPD screens. The minerals category includes all inorganic remaining materials, while the others category incorporates two noble gases (neon and argon), as well as all unknown or unspecified fractions.

Next, the composition of the output streams from Galloo was determined. Mass data on the fractions that are dismantled manually were provided, as well as on the outputs of the treatment of the OVE waste stream. This was combined with detailed knowledge on the treatment process and expert judgement of people at the company. Finally, efficiencies on two unit separation processes (see Table 3) and on the recovery of some metals when treated through shredding and mechanical separation (see Table 4) were used as well. The same separation efficiency as

Table 1: Sources for the material composition of the manually dismantled components.

Component	Material composition source
Housing desktop	Chancerel and Rotter (2009); Lee et al. (2004)
Housing laptop	Kahhat et al. (2011); von Geibler et al. (2003)
Capacitor	Hischier et al. (2007)
Transformer small	Hischier et al. (2007)
Transformer large	Gmünder (2007)
Hard disk drive	Gmünder (2007)
Power supply unit	Gmünder (2007)
Floppy disk drive	Gmünder (2007)
Compact disk drive	Gmünder (2007)
Cable small	Hischier et al. (2007)
Cable large	Hischier et al. (2007); Umicore (2013)
Printed circuit board high-grade	Umicore (2013)
Printed circuit board low-grade	Umicore (2013)
Random access memory	Hischier et al. (2007)
Processor	Hischier et al. (2007)
Cooling	von Geibler et al. (2003)
Button cell battery	Shenzen Euni Battery co. (2013)
Laptop battery	Fisher et al. (2006)
Aluminium rich fraction	Debaere (2014)
CRT screen	Hischier et al. (2007); Huisman et al. (2008)
	Nnorom et al. (2011); RepTool (2013)
LCD screen	Hischier et al. (2007); Huisman et al. (2008)
	Socolof et al. (2001)
Optical mouse	Hischier et al. (2007); Huisman et al. (2008)
Ball mouse	Hikwama (2005); Huisman et al. (2008)
Keyboard	Hischier et al. (2007); Huisman et al. (2008)

for gold and palladium is assumed for the metals present on PCBs for which no efficiency was available (Cr, Pb, Sb, Sn, and Zn).

All this information is combined to determine the path the input materials take through the process. The composition of the output fractions can thus be ascertained. These output streams are then sent to the end-processing facilities mentioned in Section 3.1.3, where the final treatment into secondary materials occurs.

The efficiency of the production process of secondary raw materials at the end-processing facility was taken into account as well, taken from various literature sources (Classen et al., 2009; Gmünder, 2007; Hischier et al., 2007; Kellenberger et al., 2007; Rentz et al., 1999; Song et al., 2013). Generally, these values are high, especially for metals in the appropriate metal smelters, with efficiencies often over 90 %.

Table 2: Materials or material categories taken into account in the material flow analysis.

Material (category)				
Fe	Pd	Sb_2O_3	Co	Hg
Al	Pb	Cr	Si	Plastics
Cu	Ni	Sn	MnO_2	Other organics
Ag	Mg	Zn	Li	Minerals
Au	Sb	Bi	Ba	Others

Table 3: Separation efficiencies of certain unit operations.

Unit operation	Separation efficiency (%)	Source
Air table separator	95	Expert judgement
Eddy current	90	Zhang et al. (1998)

Table 4: Separation efficiencies of metals treated through shredding and mechanical separation (Bigum et al., 2012).

Material	Separation efficiency (%)
Ag	12
Au	26
Pd	26
Ni	100
Fe	96
Cu	60
Al	86

The MFA on the micro-level can now be used in combination with the macro-level market analysis, to assess the total amount of materials being recovered by the recycling chain, as well as the amount of materials lost. These losses occur either through inefficiencies in the recycling chain, or because they never reach the chain.

3.4 Impact Assessment

To present the results, indicators can be utilized to quantify the benefits achieved through the management of the waste stream in a single score. Two such indicators are presented in the next sections.

3.4.1 Material Weight Recycling

The Material Weight Recycling (MWR) indicator, proposed by Nelen et al. (2014a), expresses the weight of the materials that are effectively recycled, in relation to the weight in the input, and is presented in Equation 3. This means that impurities, going to a recycling facility where they serve no purpose, are not considered, in contrast to the way this is defined in the WEEE Directive. The indicator thus determines the extent of reentry of recycled materials into the secondary raw materials market.

$$MWR = \frac{\sum_{i=1}^{m} W_i'}{\sum_{j=1}^{n} W_j} \tag{3}$$

With:

- $m =$ number of output fractions from the recycling process, destined for material recycling
- $n =$ number of materials present in the input of the recycling process
- $W_i' =$ weight of target material in output fraction i
- $W_j =$ weight of material j present in the input of the recycling process

The value of the MWR-indicator depends on which target materials are taken into account. In this way, priority materials can be defined to reflect targets for waste management, and the indicator can be calculated to show the performance accordingly.

3.4.2 Recycled Material Criticality

As mentioned in Section 1.1, the recycling of critical raw materials is important. To quantify the amount of critical raw materials recovered through the recycling process, the Recycled Material Criticality indicator (RMC) was proposed by Nelen et al. (2014a), which is presented in Equation 4. This indicator is the same as the material weight recycling indicator, with additional criticality weighting factors.

$$RMC = \frac{\sum_{i=1}^{m} W_i' \cdot EI_i \cdot SR_i}{\sum_{j=1}^{n} W_j \cdot EI_j \cdot SR_j} \tag{4}$$

With:

- $EI =$ economic importance of the material
- $SR =$ supply risk of the material

The economic importance and supply risks in Equation 4 are the values calculated by the European Commission (2014) in their criticality report. The multiplication of the two then results in the criticality value. The indicator thus represents the total input of criticality in the recycling process in the denominator, with the recovered amount of criticality in the numerator.

Only a limited amount of materials were investigated by the ad-hoc working group which compiled the critical raw materials list, and all materials not investigated receive a criticality value of zero, and are thus not taken into account in the analysis. Geological scarcity is not considered, as the time frame of the review is only ten years. The criticality of materials is also a time-dependent value, and revisions of the list are set to occur every five years.

3.4.3 Environmental Life Cycle Assessment

To assess the (environmental) performance of recycling systems, there is a need for environmentally-weighted indicators as well (Huisman et al., 2003). Therefore, life cycle assessment (LCA) is used to analyze the potential environmental impacts and resources used throughout the whole life cycle of a product (which can include goods and services), starting from the extraction of raw materials through production, use, end-of-life treatment, recycling, and final disposal. This is a comprehensive assessment and takes into account many aspects of natural environment, human health, and resource use (International Organization for Standardization, 2006).

There are many impact assessment methods through which the potential environmental burdens or benefits can be quantified. In this study, the area of protection is resource consumption, and the cumulative exergy extraction from the natural environment (CEENE) is thus used. This method uses the concept of exergy to quantify the amount of natural resources used to deliver a product. Exergy is a thermodynamic unit, which can be defined as "the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment" (Rosen and Dincer, 2001). Unlike energy, it is not subjected to a law of conservation, as it can be consumed due to irreversibilities in real processes, where it is converted to entropy. It thus can be seen as a measure of the quality of an energy form (Rosen and Dincer, 2001; Szargut, 1989; Wall, 1977).

All resources, products and waste materials have an exergy content. This can be calculated, expressed in Joule (J), and used to convert all inputs from the natural environment of the whole life cycle of a product to exergy values. Using the CEENE thus determines the fingerprint of used resources, quantified in megajoule exergy (MJex), in eight impact categories: abiotic renewable resources, fossil fuels, nuclear energy, metal ores, minerals and mineral aggregates, water resources, land and biotic resources, and atmospheric resources (Dewulf et al., 2007).

As mentioned in Section 3.2.2, two treatment scenarios for computers are considered (recycling and landfill), and the CEENE is calculated for both these scenarios, to compare the two. This shows the potential environmental benefits achieved trough recycling.

For the background system (see Section 3.2.2), no data was collected, but modeling was performed using the Ecoinvent database (Ecoinvent Centre, 2010). Some datasets were modified to better reflect the actual process, for example by changing the electricity mix to that of the appropriate country or region. Furthermore, for the production of primary bismuth, no dataset was available, so a new one was made based on data from Andrae et al. (2008).

4 Results and Discussion

4.1 Flow Analysis

4.1.1 Market Analysis

For the lifespan profile, the Weibull distribution is used, as presented in Equation 1. The values for the shape parameter $\alpha(t)$ and the scale parameter $\beta(t)$ for laptops, obtained from a Dutch case study (Wang, 2014; Wang et al., 2013) for 1995, 2000 and 2005, are assumed to be valid for Belgium, and are presented in Table 5. The values for these parameters are derived from extensive market surveys, conducted towards 5 200 Dutch households. The obtained data was then fitted to the Weibull distribution, to calculate the $\alpha(t)$ and $\beta(t)$ values.

In this study, linear regression is used to derive all values from 1995 to 2013. The resulting Weibull distribution, for laptops put on the market from 1995 to 2013 that are discarded in 2013, is shown in Figure 5.

Table 5: Values for $\alpha(t)$ and $\beta(t)$ in the Weibull distribution (Equation 1) for laptops.

	1995	2000	2005
$\alpha(t)$	1.6	1.6	1.5
$\beta(t)$	5.6	5.4	5.2

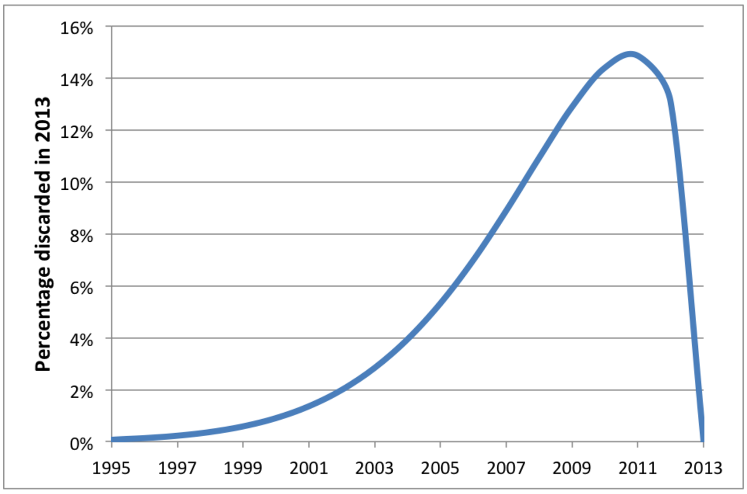


Figure 5: Weibull distribution for laptops put on the market from 1995 to 2013 and discarded in 2013.

The number of laptops, put on the Belgian market, was derived from Eurostat data, which is only available from 2007 onwards. The result of this analysis is shown in Figure 6, where the average weight reported by Chancerel and Rotter (2009) (see further in Table 6) is used to convert the number of pieces to mass. No laptops were produced in Belgium in this period, so the net POM is the difference between the imported and exported amounts.

The produced amount of waste laptops in 2013 is now calculated using Equation 2 from Section

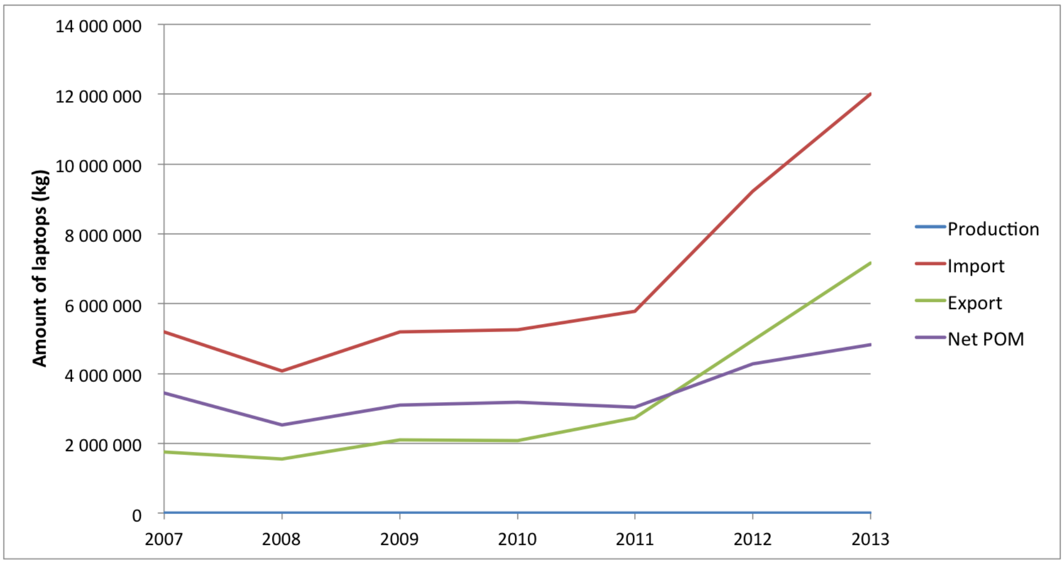


Figure 6: Amount of laptops put on the market in Belgium between 2007 and 2013.

3.3.1. The resulting amount is 2 449 256 kg waste laptops. This is a slight underestimation, as laptops put on the market before 2007 are not taken into account due to lack of data.

In 2013, Recupel collected 37 800 000 kg of the OVE-fraction, which includes the laptop computers. According to Galloo, these laptop computers constitute 0.7 % of the incoming OVE-fraction, resulting in 264 600 kg waste laptops collected by Recupel, or 10.80 % of the generated waste amount in that year.

The study on the mass balance and the market structure of (W)EEE in Belgium, performed by Huisman and Baldé (2013), investigated collection efficiencies for 2011. In this year, 41 % of the OVE stream, which contains IT equipment, was reportedly collected by Recupel, which is much higher than the calculated 10.80 % for laptops only.

This can be caused by a number of reasons. Waste laptops still have a high (material) value, which makes it financially attractive to market this waste stream outside of the Recupel system. This can include exports to developing countries, for which IT equipment is especially attractive. These exports are usually carried out illegally, so their size is difficult to quantify. Furthermore, laptops are sufficiently small to be easily kept in storage, as consumers expect them to still have a value, or possibly even even to be disposed of in normal household waste (Bisschop, 2012; Hagelüken and Meskers, 2008; Kang and Schoenung, 2005).

4.1.2 Material Flow Analysis

The next part now focuses on what happens to the waste stream that is actually collected and enters the recycling chain.

In the material flow analysis, the flux of the materials through the recycling processes was investigated. This starts at the primary treatment, where the appliances arrive to separate the different materials and send these to proper end-treatment.

As mentioned in Section 3.2.2, different appliances were taken into account: a desktop computer with peripherals (CRT or FPD screen, keyboard and ball or optical mouse), as well as a laptop computer. For these devices, average weights were used, which are presented in Table 6.

Table 6: Average masses of the appliances.

Appliance	Average mass (kg)	Source
Desktop PC tower	12.33	Chancerel and Rotter (2009)
CRT screen	14.65	Huisman et al. (2008)
FPD screen	5.28	Huisman et al. (2008)
Keyboard	1.18	Hischier et al. (2007)
Optical mouse	0.12	Hischier et al. (2007)
Ball mouse	0.13	Hikwama (2005)
Laptop	2.84	Chancerel and Rotter (2009)

The results of the analysis of the material composition of the input (from the literature sources mentioned in Table 1), as well as of the destinations after the primary treatment plant, are shown in Table 7 for desktop computers with peripherals, and in Table 8 for laptop computers. As mentioned in Section 3.3.2, these output results are obtained through a combination of analyses, expert judgement, and literature.

Graphical representations of the input of each material and the total amounts going to each end-processing treatment are shown in Figure 7 for the total waste stream, and per material category in Figure 8 for desktop and Figure 9 for laptop computers. In these figures, the precious metals category (PM) includes silver, gold and palladium, while the other non-ferrous metals class (NFe) consists out of lead, nickel, magnesium, antimony, chromium, tin, zinc, bismuth, cobalt, barium and quicksilver. Finally, Sb_2O_3, silicon, MnO_2 and lithium are added to the others category.

For desktop computers with peripherals, these results show that the main material inputs are ferrous metals and plastics (ABS) in the housing of the various parts, and the CRT glass in CRT screens. For laptops, the housing is generally built from steel, aluminium, magnesium and plastics (the copolymer acrylonitrile butadiene styrene/polycarbonate, ABS/PC), which form the main weight inputs.

The main output destinations for desktops are the steel smelter and the mineral recycler, which reflects the major input materials. In the case of laptop computers, this is more evenly distributed. The large fraction that is landfilled is the result of the fact that ABS/PC plastics are not separated for recycling, and thus partly end up in fractions to be landfilled.

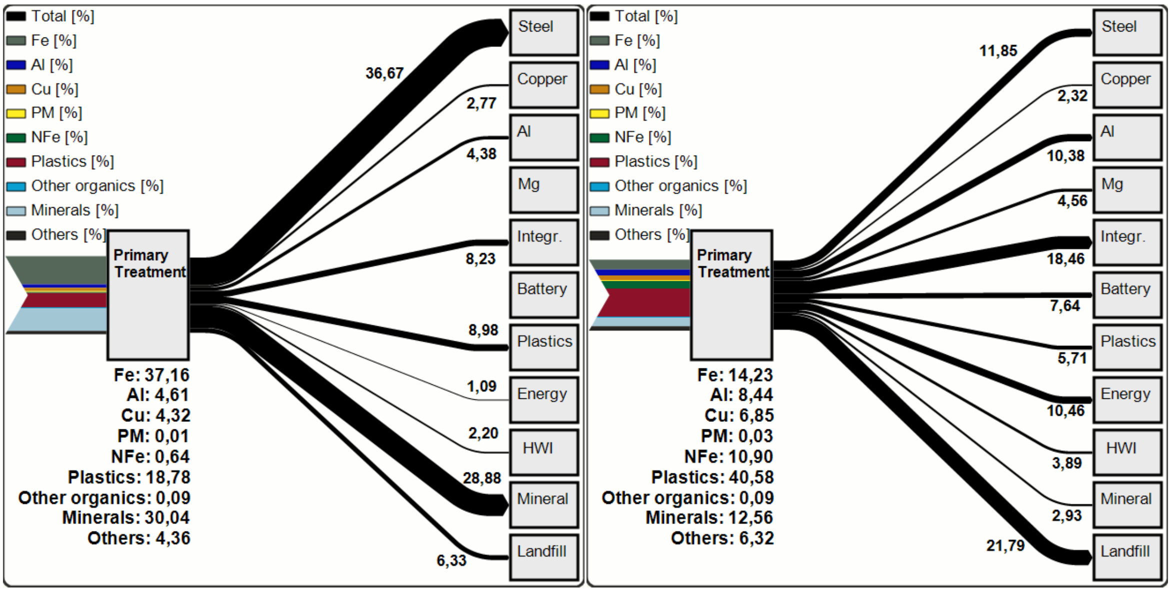
If a closer look is taken to the output destinations of the different material classes of the desktop computers, it is clear that there is not a large potential for extra recycling of ferrous metals and aluminium. This is not the case for the other materials. When PCBs are shredded, a portion of the materials is lost (see Table 4 in Section 3.3.2) to dust fractions, which are landfilled. This is especially true for precious metals. The recycling of these metals could thus be improved through an even larger dismantling depth, to manually separate more PCBs and send them to proper treatment (as suggested by Chancerel et al. (2009)), as many smaller PCBs in for instance hard disk drives are not disassembled yet. Here, the added economical cost should then be compared

Table 7: Material input and distribution of the materials over the outputs for the primary treatment of 1 000 kg desktop computers with peripherals.

	Input (kg)							Output (kg)									
	Desktop	CRT screen	FPD screen	Key-board	Optical mouse	Ball mouse	Total	Steel smelter	Copper smelter	Aluminium smelter	Integrated smelter	Plastics recycler	Energy recovery	Hazardous waste incinerator	Minerals recycler	Landfill	Total
Fe	314.0567	37.8025	8.7517	10.5561	0.3907	0.0058	371.5636	366.6505	0.8822	0.3692	1.3580			0.0038		2.2999	371.5636
Al	35.3953	9.9146	0.6815	0.0500	0.0082	0.0015	46.0510		0.1855	39.1411	2.9631			0.0316		3.7298	46.0510
Cu	23.0045	16.4558	1.5256	1.4669	0.5579	0.1940	43.2047		20.2907	0.8192	15.8781			0.0006		6.2161	43.2047
Ag	0.0606	0.0068	0.0026	0.0143	0.0023	0.0004	0.0871			0.0007	0.0373			0.0011		0.0479	0.0871
Au	0.0164	0.0004	0.0010	0.0033	0.0005	0.0001	0.0217			0.0000	0.0168					0.0049	0.0217
Pd	0.0020	0.0002	0.0002	0.0012	0.0002	0.0000	0.0037			0.0000	0.0016					0.0021	0.0037
Pb	0.6741	0.5006	0.0117	0.0350	0.0057	0.0010	1.2281			0.0501	1.0069			0.0000		0.1711	1.2281
Ni	0.3397	0.1138	0.0183	0.0875	0.0143	0.0025	0.5761			0.0114	0.5647						0.5761
Mg	0.0096						0.0096				0.0096						0.0096
Sb	0.2501	0.1001	0.0008	0.0078	0.0013	0.0002	0.3603			0.0100	0.2880					0.0622	0.3603
Sb_2O_3	0.0226						0.0226				0.0266						0.0226
Cr		0.0314	0.0004	0.0625	0.0102	0.0018	0.1064			0.0031	0.0478					0.0555	0.1064
Sn	1.7178	0.0259	0.0026	0.0525	0.0086	0.0015	1.8090			0.0026	1.3193			0.0001		0.4870	1.8090
Zn	1.2338	0.8647	0.0051	0.0350	0.0057	0.0010	2.1453			0.0865	1.5969					0.4620	2.1453
Bi		0.0314					0.0314			0.0031	0.0283						0.0314
Co																	
Si	0.0265						0.0265				0.0265						0.0265
MnO_2	1.0404						1.0404									1.0404	1.0404
Li	0.0641						0.0641									0.0641	0.0641
Ba	0.1287						0.1287				0.1287						0.1287
Hg			0.0000				0.0000									0.0000	0.0000
Plastics	53.1670	89.0893	11.3755	31.1766	2.2443	0.7195	187.7723		0.5974	2.3536	33.8224	89.7823	10.5091	21.8993	0.0374	28.7707	187.7723
Other organics	0.3005	0.1320	0.0243	0.0950	0.0704	0.2917	0.9139		0.0041	0.0132	0.2468		0.3438	0.0254		0.2806	0.9139
Minerals	17.2263	279.5033	3.6516		0.0082		300.3895			0.2367	11.3824				279.3792	9.3912	300.3895
Others	7.3757	35.0681					42.4438		5.6982	0.6827	11.5110				9.3478	15.2041	42.4438
Total	456	470	26	44	3	1	1 000	367	28	44	82	90	11	22	289	68	1 000

Table 8: Material input and distribution of the materials over the outputs for the primary treatment of 1 000 kg laptop computers.

	Input (kg)	Output (kg)											
	Laptop	Steel smelter	Copper smelter	Aluminium smelter	Magnesium smelter	Integrated smelter	Battery recycler	Plastics recycler	Energy recovery	Hazardous waste incinerator	Minerals recycler	Landfill	**Total**
Fe	142.2733	118.5423	0.0006			4.2839	16.8168					2.6297	**142.2733**
Al	84.4375		3.8329	65.6074		10.2137	3.8220					0.9615	**84.4375**
Cu	68.4772		18.7749			40.6562						9.0461	**68.4772**
Ag	0.2024					0.1195						0.0830	**0.2024**
Au	0.0785					0.0610						0.0175	**0.0785**
Pd	0.0094					0.0049						0.0045	**0.0094**
Pb	2.0714					1.8271						0.2443	**2.0714**
Ni	1.1985					1.1985							**1.1985**
Mg	83.8555			38.1776	45.6436	0.0343							**83.8555**
Sb	0.6883					0.6429						0.0455	**0.6883**
Sb_2O_3	0.2157					0.2157							**0.2157**
Cr	0.0087					0.0023						0.0064	**0.0087**
Sn	4.2869					4.0717						0.2152	**4.2869**
Zn	2.7085					2.4336						0.2748	**2.7085**
Bi													
Co	13.7592						13.7592						**13.7592**
Si	0.1733					0.1733							**0.1733**
MnO_2	1.3524											1.3524	**1.3524**
Li	2.3765						2.2932					0.0834	**2.3765**
Ba	0.4582					0.4582							**0.4582**
Hg	0.0000											0.0000	**0.0000**
Plastics	405.8136		0.6052			44.8160		57.0568	104.6307	38.7799		159.9250	**405.8136**
Other organics	0.8737					0.1160			0.0005	0.1344		0.6228	**0.8737**
Minerals	125.6313					53.3419	9.9372				25.6555	36.6967	**125.6313**
Others	59.0499					19.8868	29.8115				3.6174	5.7341	**59.0499**
Total	1 000	119	23	104	46	185	76	57	105	39	29	218	**1 000**



(a) Desktop computers **(b)** Laptop computers

Figure 7: Input of each material category in the end-of-life product and distribution at the primary treatment step to the end-processing stage for desktop computers with peripherals and laptop computers, in mass percent. Steel: steel smelter; Copper: copper smelter; Al: aluminium smelter; Mg: magnesium smelter; Integr.: integrated smelter; Battery: battery recycler; Plastics: plastics recycler; Energy: energy recovery; HWI: hazardous waste incinerator; Mineral: minerals recycler; Landfill: landfill deposition.

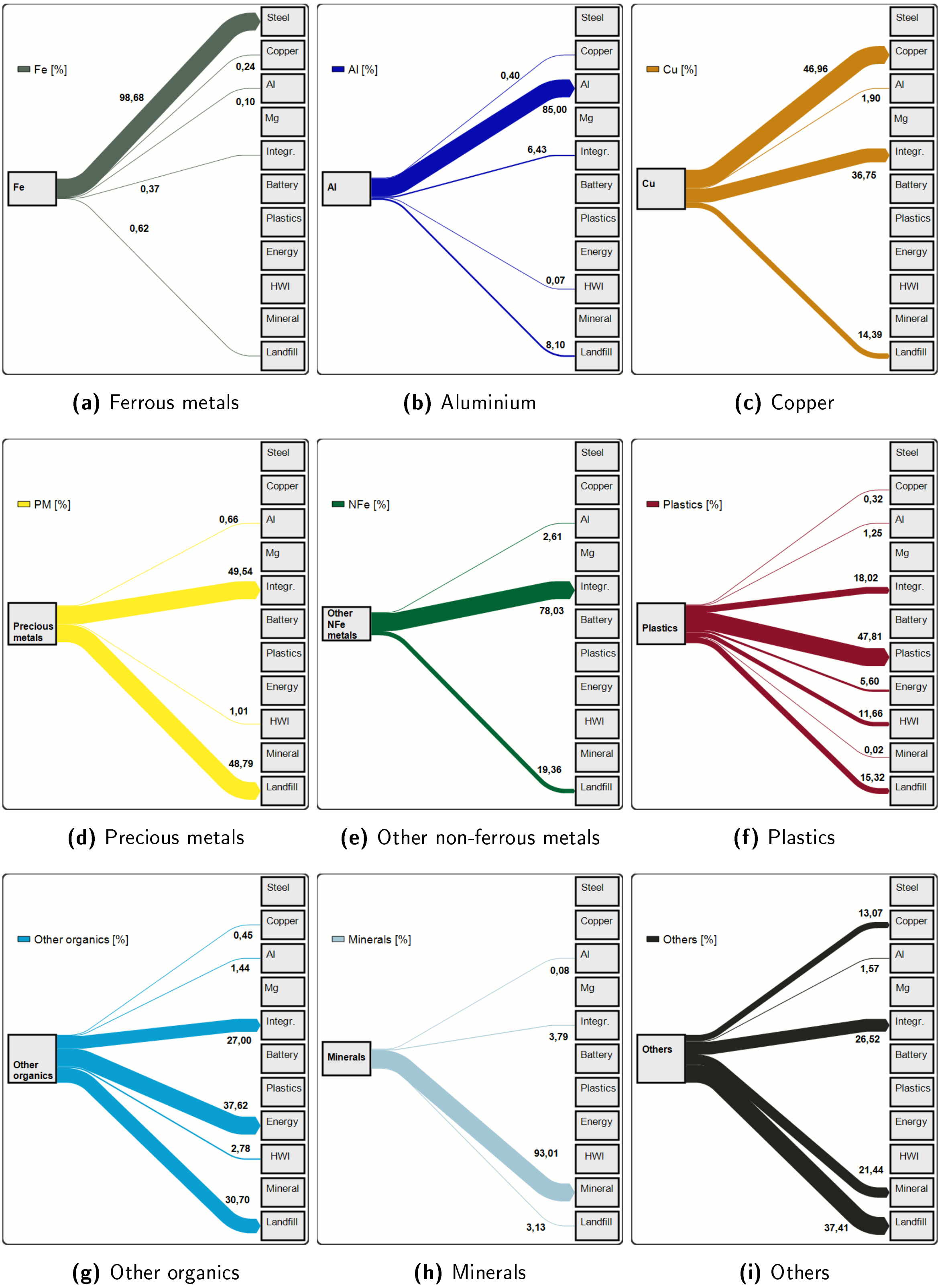
to the achieved extra economical and environmental gains. For laptop computers, a similar pattern is observed.

In the assessment of the input materials, no rare earth elements or certain other valuable materials, such as tantalum or indium, were taken into account, as they were not included in the composition analysis due to lack of data, and obtaining quantitative information on these elements is challenging. However, these materials are present in computers, which could form a valuable source for recovery through recycling, although this is not yet widely performed to date.

4.2 Material Weight Recycling

The amount of materials effectively recycled by the recycling chain (taking into account the recycling efficiencies at the end-processing step) of desktop computers with peripherals and laptop computers is presented in Table 9. In this table, the MWR-indicator is calculated for each material separately, and for the total waste stream. Recovery of materials for a different use as was originally the case, such as the use of smelter slags as a construction material or organic impurities as fuel, is not regarded as material recycling and is thus not included in the MWR-indicator.

This shows that 48.63 % of the materials in desktops with peripherals and 39.43 % of the materials in laptops are effectively recycled to form secondary raw materials. These rather low numbers are caused partly by the low recycling rates for plastics. There are many different polymers present in the waste stream, and effective separation thereof is challenging (Hopewell et al.,

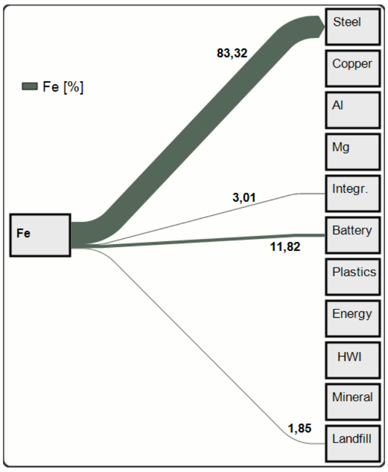


(a) Ferrous metals **(b)** Aluminium **(c)** Copper

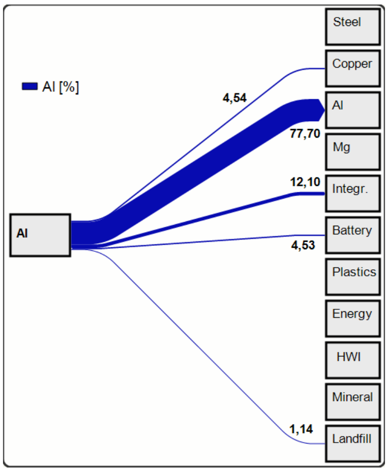
(d) Precious metals **(e)** Other non-ferrous metals **(f)** Plastics

(g) Other organics **(h)** Minerals **(i)** Others

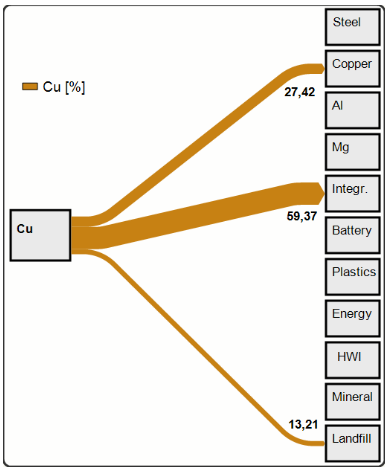
Figure 8: Distribution of the different material categories at the primary treatment step to the end-processing stage, for desktop computers with peripherals, in mass percent. Steel: steel smelter; Copper: copper smelter; Al: aluminium smelter; Mg: magnesium smelter; Integr.: integrated smelter; Battery: battery recycler; Plastics: plastics recycler; Energy: energy recovery; HWI: hazardous waste incinerator; Mineral: minerals recycler; Landfill: landfill deposition.



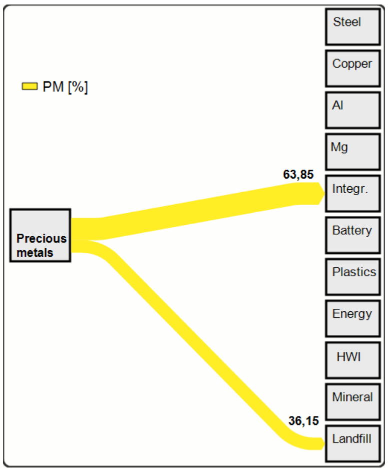
(a) Ferrous metals



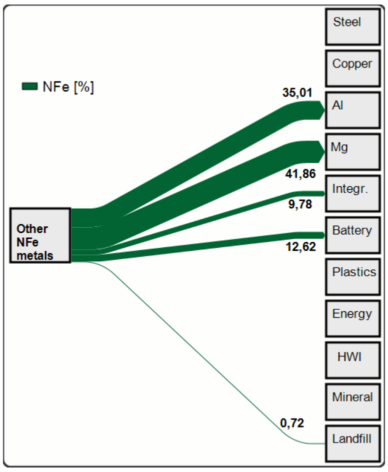
(b) Aluminium



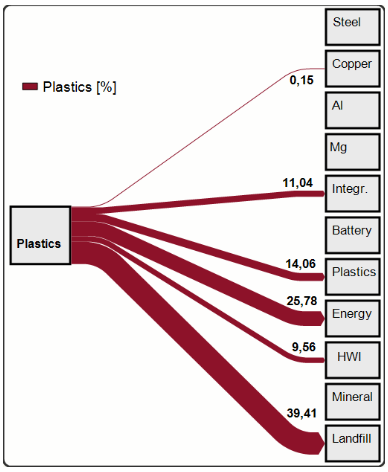
(c) Copper



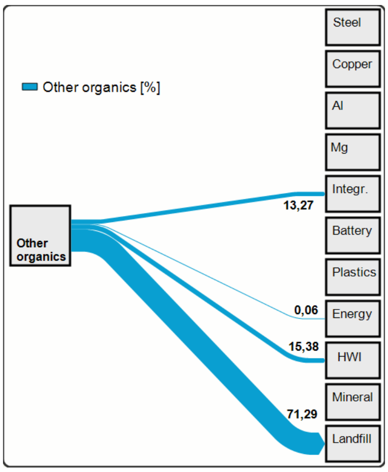
(d) Precious metals



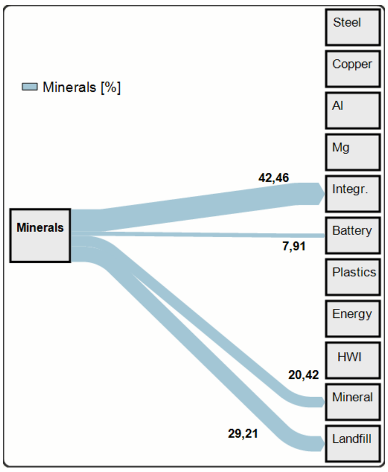
(e) Other non-ferrous metals



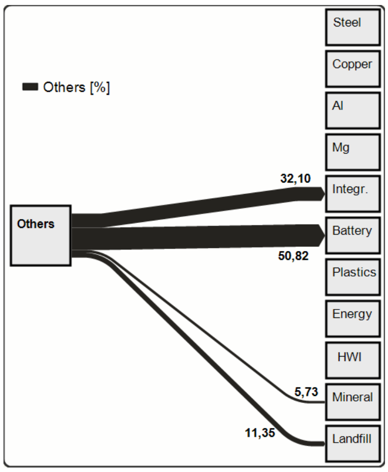
(f) Plastics



(g) Other organics



(h) Minerals



(i) Others

Figure 9: Distribution of the different material categories at the primary treatment step to the end-processing stage, for laptop computers, in mass percent. Steel: steel smelter; Copper: copper smelter; Al: aluminium smelter; Mg: magnesium smelter; Integr.: integrated smelter; Battery: battery recycler; Plastics: plastics recycler; Energy: energy recovery; HWI: hazardous waste incinerator; Mineral: minerals recycler; Landfill: landfill deposition.

Table 9: Effective material recycling per 1 000 kg desktops with peripherals or laptops treated, and the Material Weight Recycling (MWR) indicator.

	Desktop with peripherals			Laptop		
	Input kg	Recycled kg	MWR %	Input kg	Recycled kg	MWR %
Fe	371.5636	331.8104	89.30	142.2733	122.4969	86.10
Al	46.0510	38.0011	82.52	84.4375	63.6965	75.44
Cu	43.2047	33.7176	78.04	68.4772	58.3597	85.22
Ag	0.0871	0.0370	42.44	0.2024	0.1183	58.43
Au	0.0217	0.0166	76.61	0.0785	0.0604	76.88
Pd	0.0037	0.0016	42.64	0.0094	0.0049	51.86
Pb	1.2281	0.5035	40.99	2.0714	0.9135	44.10
Ni	0.5761	0.4518	78.42	1.1985	0.9588	80.00
Mg	0.0096	0.0000	0.00	83.8555	81.3798	97.05
Sb	0.3603	0.2304	63.96	0.6883	0.5143	74.72
Sb_2O_3	0.0226	0.0000	0.00	0.2157	0.0000	0.00
Cr	0.1064	0.0000	0.00	0.0087	0.0000	0.00
Sn	1.8090	0.6597	36.46	4.2869	2.0358	47.49
Zn	2.1453	0.0000	0.00	2.7085	0.0000	0.00
Bi	0.0314	0.0226	72.00	0.0000	n/a	n/a
Co	0.0000	n/a	n/a	13.7592	12.3832	90.00
Si	0.0265	0.0000	0.00	0.1733	0.0000	0.00
MnO_2	1.0404	0.0000	0.00	1.3524	0.0000	0.00
Li	0.0641	0.0000	0.00	2.3765	0.0000	0.00
Ba	0.1287	0.0000	0.00	0.4582	0.0000	0.00
Hg	0.0000	0.0000	0.00	0.0000	0.0000	0.00
Plastics	187.7723	80.8849	43.08	405.8136	51.4026	12.67
Other organics	0.9139	0.0000	0.00	0.8737	0.0000	0.00
Minerals	300.3895	0.0000	0.00	125.6313	0.0000	0.00
Others	42.4438	0.0000	0.00	59.0498	0.0000	0.00
Total	1 000	486	48.63	1 000	394	39.43

2009). Moreover, only five polymers (PP, PS, PE, ABS and PMMA) are recycled to new plastics pellets. The CRT-glass, which is a part of the Minerals category, also causes the MWR-indicator to be low.

Therefore, if only metals of which the recycling is possible in the used end-processing treatment are taken into account, the MWR-indicator increases to 86.78 % for desktops and 84.87 % for laptops.

4.3 Resource Potential

The results of the macro-level market analysis can now be coupled with the micro-level material flow analysis for laptop computers, to determine the resource potential of waste laptops in Belgium (264 600 kg collected by Recupel in 2013), when extrapolating the process at Galloo. Taking into account the recycling efficiencies at the end-processing stages, the amount of resources recycled from the collected waste laptop stream is shown in Table 10.

Table 10: Effective recycling for each recycled material, in kilogram per 264 600 kg waste laptops collected by Recupel.

	Fe	Al	Cu	Ag	Au	Pd	Pb	Ni	Mg	Sb	Sn	Co	Plastics
Recycled	32 413	16 854	15 442	31	16	1	242	254	21 533	136	539	3 277	13 601
Potential	348 464	206 809	167 718	496	192	23	5 073	2 936	205 384	1 686	10 500	33 700	993 942
Percentage	9.30	8.15	9.21	6.31	8.31	5.60	4.76	8.64	10.48	8.07	5.13	9.72	1.37

Furthermore, the total amount of these materials, enclosed in the total waste laptops stream in 2013 (amounting to 2 449 256 kg), is presented as well, as the entire potential for material recycling from this waste stream for these materials, in case the whole waste steam would be collected by Recupel and treated by Galloo. The reason this potential is not reached is twofold: because only about 10.80 % is collected and enters the recycling chain, and because of losses due to inefficiencies in the recycling chain itself. In case the recycling chain had an efficiency of 100 %, the highest possible recycling percentage would thus be 10.80 %. The percentage in Table 10 does not necessarily represent the recycling rate of these materials in the Belgian recycling chain, as WEEE not collected by Recupel can be treated through a different process or at a different location as well, but merely displays the share recovered through Recupel.

This material recycling is carried out for 19 % in Belgium, 57 % in the rest of the EU, and the remaining 24 % in the rest of the world. All precious metals and most other non-ferrous metals are processed in Belgium, while only aluminium, magnesium and PMMA have a significant recycling share outside the EU. The majority of the materials are thus recycled in the EU, which keeps these resources within the European market. This means that recycling can play a major role in making the EU less dependent on imports for raw materials.

4.4 Recycled Material Criticality

The European Commission (2014) determined the economic importance and supply risk (which together form the criticality) of a set of raw materials. These values can be found in the annexes to their report. This can be combined with the material recovery results, to assess the recovery of critical raw materials by the recycling system.

First, all materials assessed by the European Commission are taken into account. These results show that for desktops the only significant criticality inputs are ferrous metals (85 %), aluminium (9 %), and copper (3 %). Criticality is therefore recovered to a large extent, as these materials are recycled effectively. For laptops, magnesium (51 %), available in the housing, is the most important input, followed by ferrous metals (23 %), aluminium (12 %), cobalt (7 %), and copper (4 %). These materials are mostly recycled as well. In general, this means that recycling desktops and laptops achieves a large recovery of criticality. Thus, the calculated values for the total RMC-indicator are 87 % and 89 % for desktops and laptops, respectively.

Second, the indicator is calculated using only the materials deemed critical by the European Commission (of which Pd, Mg, Sb, Cr, Sn, Co, and Si are present in the input analysis of this study). This results in an RMC-indicator amounting to 43 % for desktops. The critical materials input is mainly formed by tin (58 %) and antimony (35 %). In the case of laptops the overall

RMC-indicator value is 95 %, which is caused by the high shares of magnesium (86 %) and cobalt (11 %) in the input, as these two materials have a high recycling efficiency.

However, the selection of the materials which are to be assigned the 'critical' label is open for discussion. The assessment of the European Union depends on fixed thresholds for both the economic importance and supply risk parameters, which form a rectangular 'critical region'. This approach is subject to debate, as the criticality concept stems from classical risk assessment, with a probability dimension (cfr. supply risk) and a consequence dimension (cfr. economic importance). The product of the two dimensions then yields the overall risk, or criticality of the raw material, as implemented in the indicator of Nelen et al. (2014a). The graph of this product describes hyperbolic contour lines with equal criticality values, as opposed to the rectangular region in the report of the European Commission. This leads to raw materials with the same criticality value (on the same contour line) being classified differently by the European Commission, as they do not both lie within or out of the rectangular critical region (Glöser et al., 2015).

Additionally, not all materials deemed critical by the European Commission were present in the analyses of the input composition, such as rare earth metals in hard disks and indium in screens, which may cause an underestimation of the calculated data. On the other hand, these materials are present in very low quantities compared to the main inputs, and thus will have a low impact on the value of the RMC-indicator taking into account all analyzed materials, as well as on the indicator only assessing critical materials in the case of laptops. For the latter indicator for desktop computers, this lack of input data could be more influential.

The high values of these indicator results do not mean that no further efforts regarding the recycling of critical raw materials should be made. Many of these materials are vital to the economy, but currently have recycling rates below 1 % (UNEP, 2013), as the recycling processes of these materials are not (yet) technically feasible or economically attractive (Chancerel et al., 2015).

4.5 Environmental Life Cycle Assessment

4.5.1 Environmental Impacts of the Recycling Chain

As the focus of this study is resource use, the environmental impact considered is resource use, quantified by the CEENE. The results of the CEENE analysis for the recycling chain for each treatment step (collection, primary treatment (dismantling and mechanical separation) and end-processing) are presented in Figure 10. It is clear from this figure that in the recycling chain of desktop computers with peripherals, as well as for the treatment of laptop computers, the end-processing step, where the secondary materials are produced, has by far the biggest CEENE-impact, compared to the impact of the collection and primary treatment (dismantling and mechanical separation) steps. The different treatment stages will now be discussed separately.

Collection The impact of the collection step is caused only by the transport activities, as the receptacles for collection are reused and last a very long time. They are thus not taken into account. As can be expected, the fossil fuels impact category is by far the most important for the collection step. The impact is the same for both desktop and laptop computers, as in both the cases the functional unit is 1 000 kg of waste material, and the transported distance is assumed to be equal for both streams.

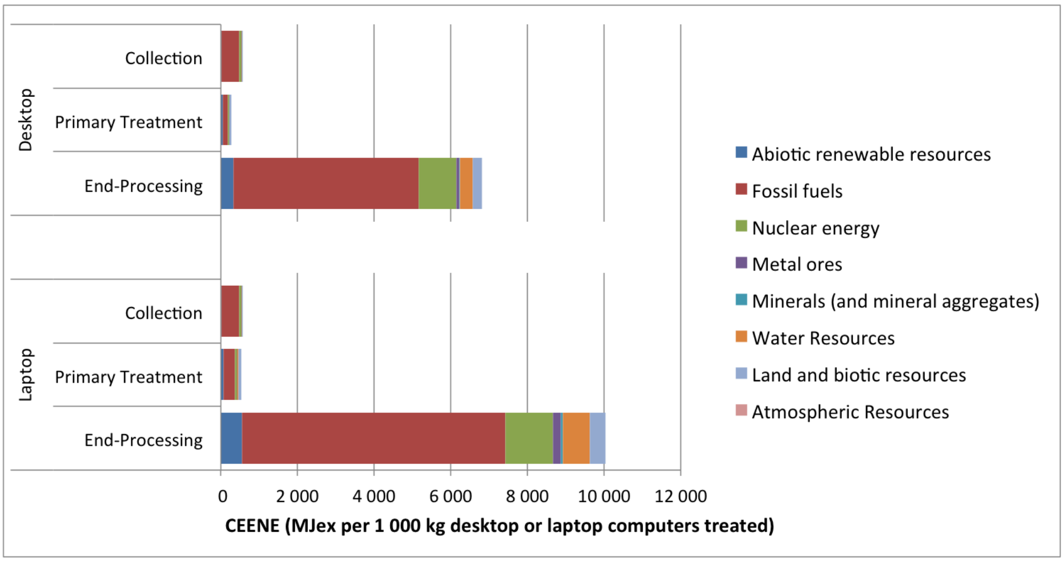


Figure 10: Results of the CEENE analysis for the recycling chain of desktop computers with peripherals and laptop computers, per treatment step.

Other scenarios for the transport distance can be investigated as well, as this distance is based on an estimation, mentioned in Section 3.1.1. The impact of transport is directly proportional to the distance covered, so when the distance increases, the associated impact will increase accordingly. This means that even if the transport distance would double or triple, the collection still would have a far smaller impact than the end-processing step.

Primary Treatment The impact for the primary treatment is presented in Figure 11. Here, the Chemicals category includes the density media and the binding agent, while the Disposal category covers various landfill disposal processes for waste fractions leaving Galloo. These results differ for desktop and laptop computers.

The biggest impact for the desktop computers with peripherals is caused by the use of the chemicals (around 73 %), which causes mainly fossil fuels and metal ores consumption. Other utilities cause only minor impacts. The required electricity is produced with biogas from a digestion plant mainly treating agricultural waste. Therefore, the impact of the electricity consumption is small. In case the electricity would be delivered by the Belgian electricity mix, the impact of the electricity use increases about sixfold, however this does not significantly change the results of the total recycling chain.

The impacts caused by the treatment of laptop computers are dominated by the chemicals category as well (around 68 %). In comparison to the desktop computers, the disposal operations of waste fractions from Galloo have a higher impact (around 23 %), mainly as the housing of a laptop has a higher plastics share (see Table 8), part of which is lost in a waste stream in the main OVE treatment system.

When the primary treatment of desktop computers with peripherals is compared with that of laptop computers, Figure 11 shows that the latter requires more natural resources than the former. This is caused by the fact that laptops are more compact and high-grade appliances.

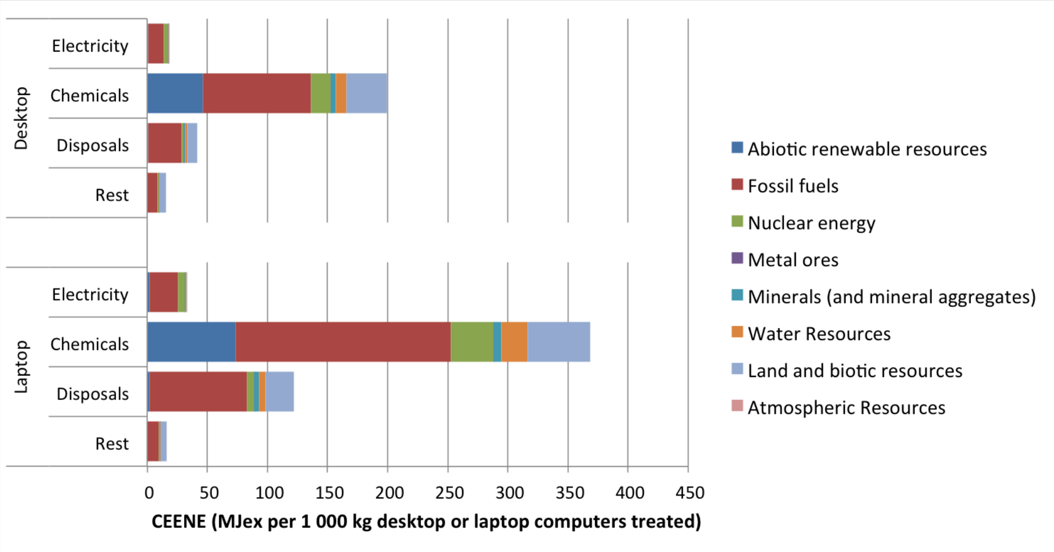


Figure 11: Results of the CEENE analysis for the primary treatment at Galloo of desktop computers with peripherals and laptop computers.

The CRT glass in CRT screens for example constitutes a large share in weight of the desktop computers, but is separated immediately, and thus does not require further processing in the primary treatment step.

End-Processing The results for the end-processing treatment steps for desktop computers with peripherals, and laptop computers, are presented in Figure 12.

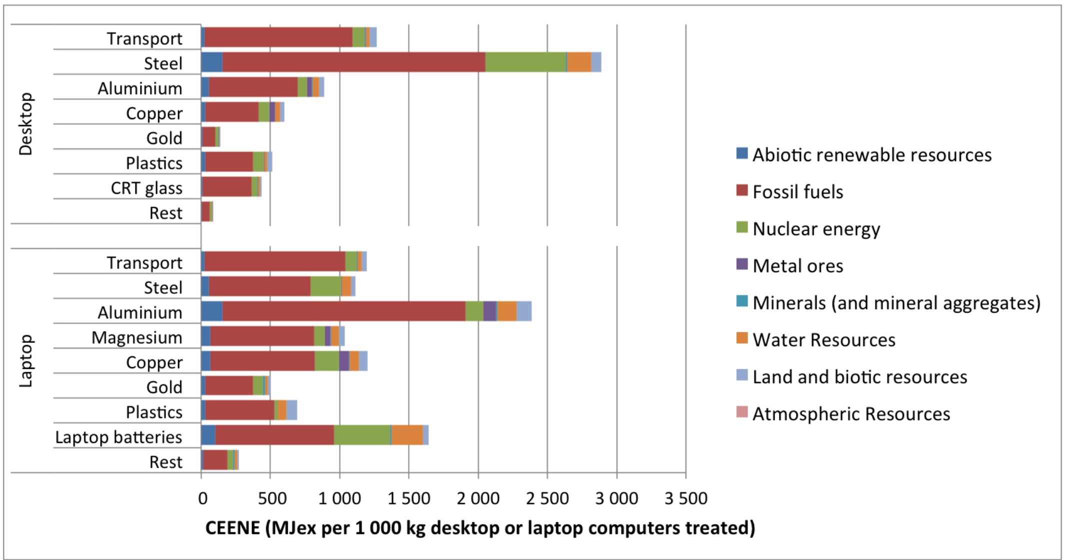


Figure 12: Results of the CEENE analysis for the end-processing of the materials separated form desktop computers with peripherals and laptop computers.

The end-processing impacts of the materials originating from the desktop computers are caused mainly by the production of secondary steel (around 42 %), because of the large steel content of the appliances. This is composed to a large extent of fossil fuels and nuclear energy consumption, arising because of the large energy requirements of a metal smelter. Transport to the end-processing facility is responsible for the second largest share (around 19 %), almost completely relying on fossil fuels consumption.

Next, secondary aluminium and copper production are responsible for the largest impacts (around 13 % and 9 % respectively), with a main contribution for fossil fuels consumption as well. Finally, the secondary plastics production and the treatment of the CRT glass cause around 8 % and 6 % of the impacts respectively, again mainly using fossil fuels. The rest of the operations only contribute to a minor extent, because of the small amounts treated (e.g. gold), or the small impact of the treatment itself (e.g. slag cement).

Second, for laptops the main impact is the secondary production of aluminium (around 24 %), because there is a lot more of it present in laptops, compared to desktops, and because part of the magnesium fraction is treated in aluminium smelters as an alloying element, which causes an extra mass to be treated there. The large energy requirements of the smelter cause the impact to be constituted mainly out of fossil fuels consumption.

Next, the treatment of the laptop batteries is responsible for around 16 % of the impacts, mainly composed of fossil fuels, nuclear energy and water resources consumption. This is caused by the extensive energy requirements, and the use of sodium hydroxide in the treatment process. The transport, almost exclusively because of fossil fuels consumption, has a share of around 12 %, whereas the percentage of the production of copper, steel and magnesium amounts to around 12 %, 11 % and 10 %, respectively. These all have similar consumption patterns, related to the use of metal smelters.

Finally, the production of secondary plastic pellets, which needs significant energy to remelt the polymers, and secondary gold, with substantial energy requirements as well, amount to 7 % and 5 % respectively. These energy needs again induce mainly fossil fuels consumption.

Notable differences between the treatment of desktop computers with peripherals, compared to laptop computers, is first of all the larger impact for secondary steel manufacturing with the former, caused by the larger steel content of desktop computers. The same reasoning applies for aluminium, in the case of laptops. For these appliances, magnesium and batteries are processed as well, causing quite some impact, which is not the case for desktop computers. Finally, the larger gold content of laptop computers means that the impact of the secondary processing thereof is significantly bigger.

4.5.2 The Recycling Chain Compared to Landfill

The results of the impact assessment for the landfill scenario are presented in Figure 13. These impacts are caused by the landfill disposal activity itself, as well as by the manufacturing from virgin resources of the same products, as produced by the recycling chain.

For desktop computers with peripherals, steel again has the biggest share of the impacts (around 23 %), but the difference with other metals like aluminium (around 22 %) and gold (around 18 %) is much smaller, because the difference between primary and secondary production of steel is smaller, compared to the other metals. The impact of the production of ABS is large as well

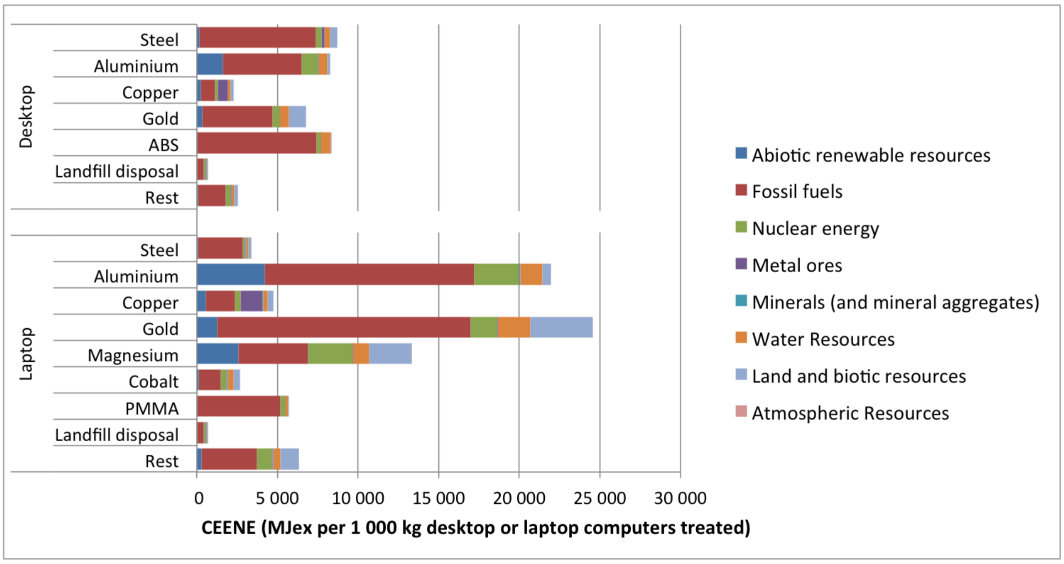


Figure 13: Results of the CEENE analysis for the landfill scenario.

(around 22 %), almost completely based on fossil fuels consumption, because of the utilization of these resources as the starting product. The resource impact of the landfill disposal activity itself is small (around 2 %), compared to the material manufacturing.

In the case of laptop computers, the primary gold production has the biggest impact (around 29 %), because of the large impact of mining, refining and smelting of gold ore, resulting mainly in fossil fuels consumption. Besides that, the impact of aluminium is important (around 26 %), as well as the one of magnesium (around 16 %). The plastic PMMA, present in the backlight of FPD screens, causes around 7 % of the impacts, almost exclusively from fossil fuels consumption. The impact of the landfill disposal itself is again insignificant.

The comparison of both scenarios for the treatment of waste desktop and laptop computers is shown in Figure 14. For the recycling scenario, no virgin material production is thus taken into account. It is clear, for desktop computers with peripherals as well as for laptop computers, that the recycling of these appliances is largely beneficial compared to landfilling the waste stream, from a resource consumption perspective.

The difference between the two scenarios is especially large for laptop computers. This is because these devices are smaller and more compact, with a larger concentration of valuable resources. The recycling of these appliances therefore has a larger impact, compared to the one for desktop computers with peripherals, but this scenario also achieves a much larger avoided burden. So although in the case of laptops a smaller percentage of the materials is recovered (see Section 4.2), the avoided burden achieved trough this recovery is higher.

It therefore can be concluded that for waste desktop computers with peripherals and waste laptop computers, the recycling is to be preferred over landfilling, from a resource consumption point of view. The recycling of the former saves 80 % of the resources, while for the latter this is 87 %.

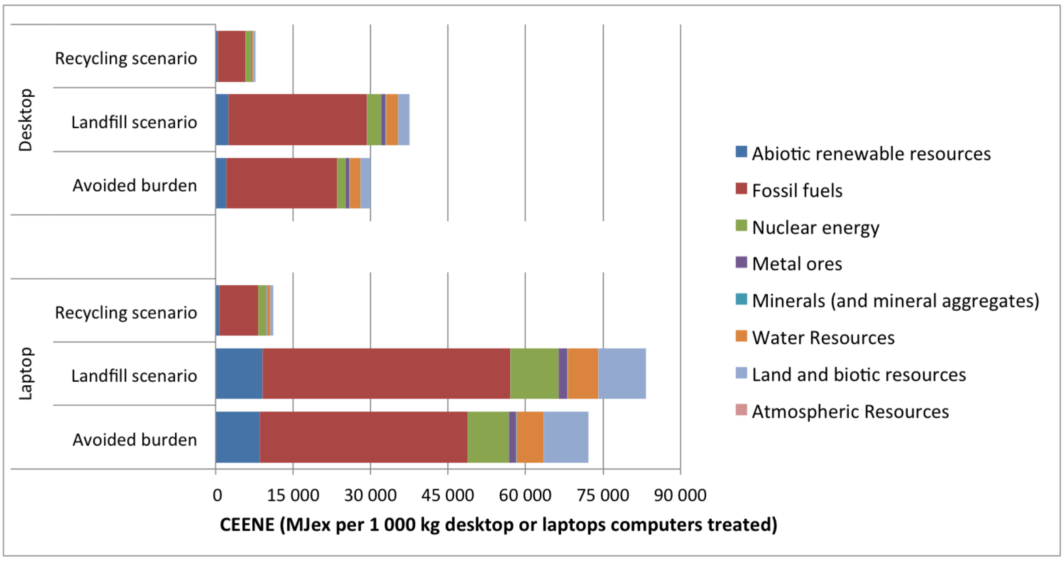


Figure 14: Comparison of the CEENE analysis for the recycling and landfill scenario.

4.6 Comparison with Previous Study

A previous study assessing the recycling of WEEE in Belgium was carried out by Nelen et al. (2014b). Here, two waste streams were investigated, that is Large white goods and IT equipment. The results of this study, assessing desktop and laptop computers, could thus be compared to the results for the product category of IT equipment. The latter category contains, in addition to computers, accessories, phones, printers, copy machines, gaming computers, and similar appliances.

For the market analysis, the numbers from the mass balance for the Belgian WEEE treatment system from Huisman and Baldé (2013) were used, although no separate IT equipment stream is distinguished there. IT is part of the OVE stream, for which a collection efficiency of 41 % is reported (see Section 4.1.1). The authors mention that for IT equipment, this is probably lower, and would decrease even more in the case of computers. This is thus in line with the collection result of 10.80 %, calculated in the market analysis in this study.

For the composition of the input material, Nelen et al. (2014b) use a general composition analysis for IT equipment reported in Huisman et al. (2008), while this study makes use of detailed bottom-up compositions of the specific desktop and laptop computer components. Furthermore, desktop screens (CRT and FPD) were included in the present study, but are not part of the IT equipment category used by Nelen et al. (2014b).

The effective recycle rates for each material were calculated as well, also by modeling the complete recycling processes, and most of these results for the single materials are in the same range as the ones obtained in this study. Some are markedly higher though, especially the ones for precious metals, ranging from 70 % to 85 %, which can be due to the significant percentage of high-grade PCBs (such as in mobile phones) which are treated in an appropriate smelter directly, and because of differences in assumptions when modeling the recycling process. Furthermore, the recycling rate of the plastic polymer ABS/PC is calculated to be 87 % by Nelen et al. (2014a), whereas no recycling takes place according to this study.

Overall, a recycling efficiency of 85 % is calculated for the IT equipment category, compared to 49 % and 39 % for desktops and laptops respectively. This discrepancy is caused by the aforementioned differences in recycling rates for the single materials, but more importantly by the difference in the composition of the input material. This can be illustrated using the examples of steel and CRT glass. The much higher content of the former, which is a material with a very high recycling rate, in the study by Nelen et al. (2014b) causes the overall recycling efficiency to increase accordingly, whereas the latter, with a significant input share in this study and no recycling, is not present in the IT equipment category, and thus does not reduce the overall recycling rate in the study of Nelen et al. (2014b).

A (simplified) LCA was also carried out, only taking into account the avoided burden of the primary production of materials recovered through the recycling process. The impact of the recycling process itself was thus not considered. Furthermore, only the benefits of material recycling were taken into consideration, although downcycling was considered for inert materials and glass ending up in the residual rest fraction reused in construction materials, and further tackled by a specific indicator on cycle closure. The net scrap method used in the study by Nelen et al. (2014b) only grants environmental benefits for the recycling of the material share that exceeds the recycled content already present in the input material. Therefore, the environmental benefits attributed to the recycling of materials with an already high recycled content, such as copper (35 % recycled content) and palladium (68 % recycled content), will be lowered. This method will thus award the recycling of materials that still present a low share of secondary content with relatively higher benefits.

The impact was assessed using the ReCiPe method, which takes into account various impacts to human health, ecosystems and resource consumption, which can be combined into one score. Although in this study a different impact assessment method was used (CEENE), the results can nonetheless be compared (Huijbregts et al., 2010). The reported avoided burden through the recycling of IT equipment in general is 68 % to 72 %, depending on the method used, and is thus lower than the one for desktop and laptop computers obtained in this study (80 % and 87 %).

For the criticality assessment, Nelen et al. (2014b) report a recovery of criticality of 94 %, which is even higher then the 87.25 % and 87.54 % calculated in this study. This could be due to the larger steel content in IT equipment, as this material forms 94 % of the recovered criticality. The previous criticality assessment by the European Commission from 2010 was also used, which took into account fewer materials.

5 Conclusion

In this study, the recycling of desktop computers with peripherals and laptop computers was assessed, on different levels and with different methods.

First, a market analysis on the macro-level revealed that in 2013 approximately 10.80 % of the waste laptop computers in Belgium were collected by Recupel. A large part of the waste stream is thus still treated in potentially sub-optimal circumstances. This demonstrates that the collection step is the bottleneck in the recycling chain, and consumers thus should continuously be encouraged to dispose their waste appliances through the appropriate channels.

Next, a material flow analysis on the micro-level assessed the inputs of the different materials to the recycling chain, and to what extent these are effectively recycled to produce secondary raw materials. This showed that especially for precious metals, improvements still can be made in the recovery efficiency. This can be done through an increase in the manual dismantling depth, although the resulting extra environmental and economic benefits have to be weighed up to the increased economic costs.

The recycling of laptops in Belgium achieves production of secondary resources, amounting to among others 32 tonnes of steel, 17 tonnes of aluminium, 15 tonnes of copper, 14 tonnes of plastics, and 48 kg of precious metals.

For desktop computers, 48.63 % of all materials and 86.78 % of metals, of which the recycling is possible at the considered end-processing facilities, are effectively recycled. For laptops, these values are 39.43 % and 84.87 %, respectively. This material recycling can also be weighted, to express the amount of criticality that is recovered. This criticality is the result of the economic importance and supply risk of a material. For desktops, 87.25 % of the critical mass is recovered, while for laptops this is 89.34 %, if all analyzed materials are taken into account, whereas these numbers amount to 43 % and 95 % respectively, when only the critical raw materials are considered. This does not mean however that no further efforts regarding the recycling of critical raw materials should be made, as many of these materials are vital to the economy, but currently have recycling rates below 1 %. Furthermore, the concept of critical raw materials is fairly novel, and the methods have not been consolidated yet, so further methodological progress is needed as well.

The environmental impact of the recycling chain was assessed as well, and compared with the scenario where the waste stream is landfilled and the secondary produced materials are manufactured through the primary production chain. These impacts were expressed in CEENE, which determines the resource footprint of a product.

This showed that in the recycling chain for both desktops and laptops, the end-processing step, where the secondary raw materials are produced, has by far the largest impact, compared to the collection and primary treatment. These end-processing impacts are, in the case of desktops, largely caused by the production of secondary steel, while for laptops, the most important processes are production of secondary aluminium and the recycling of the batteries.

These impacts of the recycling chain are much smaller than the impacts of the primary production of the recovered materials (80 % and 87 % less resource consumption, in the case of desktops and laptops respectively). For desktops, the impacts of the landfill scenario are mainly caused by the production of steel, aluminium, gold, and ABS, while for laptops, the production of gold and aluminium are the most important.

These results highlight that the current recycling targets of WEEE in the EU do not promote the recovery of metals present in minor amounts, despite their clear environmental and economic relevance. To further advance the recycling of WEEE, this type of results could be used for various aims. They allow to more systematically identify where the losses of resources occur, and how these losses could be reduced (e.g. by intervention on policies on the product design level, see e.g. Ardente and Mathieux (2014), or on the end-of-life level, e.g. recycling targets for individual materials). Furthermore, it could help to set-up a database of robust and representative data of recycling rates of materials and components contained in specific product groups, as recommended by Ardente and Mathieux (2012).

For future research, new analyses of product material compositions are needed to increase the accuracy of the results, as the material composition has a large influence on the achieved benefits. This can also better highlight the resource potential of waste appliances in Belgium. Consequently, a better understanding of the recycling market, and the waste streams that are not collected, is needed as well.

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