Resources, Conservation and Recycling 107 (2016) 53–64

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

# Resource savings by urban mining: The case of desktop and laptop computers in Belgium

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ARTICLE INFO

*Article history:*
Received 10 July 2015
Received in revised form 28 October 2015
Accepted 29 October 2015

*Keywords:*
WEEE
Recycling
Raw material criticality
MFA
LCA

## ABSTRACT

Waste electrical and electronic equipment (WEEE) has become increasingly important over the last years. Additionally, the European Union recognizes the growing importance of raw materials, and the crucial role of recycling. In this study the performance of WEEE recycling was assessed for the case of desktop and laptop computers in Belgium in 2013. The analysis was performed in four steps. First, the recycling chain is analyzed through material flow analysis (MFA) at the level of specific materials. Second, an indicator is calculated, which quantifies the effectively recycled weight ratios of the specific materials. Third, a second indicator expresses the recycling efficiency of so-called critical raw materials. Finally, the natural resource consumption of the recycling scheme in a life cycle perspective is calculated using the Cumulative Exergy Extraction from the Natural Environment (CEENE) method, and is benchmarked with a landfill scenario. Overall, the results show that base metals such as ferrous metals, aluminium and copper are recycled to a large extent, but that for precious metals improvements still can be made. The input of criticality (arising from the incoming mass, as well as the individual criticality value of the assessed material) mainly comes from base metals, resulting in a high recovery performance of raw materials criticality. Finally, the natural resource consumption of the recycling scenario is much smaller than in case of landfilling the WEEE: 80 and 87% less resource consumption is achieved for desktops and laptops respectively, hence saving significant primary raw materials.

## 1. Introduction

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, and furthermore, due to ongoing technological innovations, lifespans decrease and consumer demand increases continuously. This in turn gives rise to increasing WEEE quantities being disposed of by the users (Wang et al., 2013; Widmer et al., 2005).

Because of the complex composition of electronic appliances, recycling has a twofold purpose. WEEE 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 are 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 Europe, so their availability is coming increasingly under pressure. An assessment of the economic criticality was therefore made, based on the economic importance and supply risk of 54 non-energy and non-agricultural raw materials, resulting in 20 raw materials being identified as critical (European Commission, 2014).

To enhance the recovery, the European Union (EU) adopted the WEEE Directive in 2002 to improve the collection, which is a major bottleneck (Bernstad et al., 2011), and subsequently the efficiency of the total recycling chain for WEEE. The WEEE Directive has been

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http://dx.doi.org/10.1016/j.resconrec.2015.10.032

recast in 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/cap), 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. 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 (European Parliament and Council, 2012).

The choice of the directive for a focus on overall mass means that the recyclers can concentrate on the materials which are present in large amounts in the waste stream, such as ferrous metals or plastics, to achieve the imposed targets. In this situation, materials existing in small quantities, like precious metals, can potentially be neglected despite their obvious environmental and economic relevance. However, their primary production causes large environmental impacts, and recycling these materials could therefore achieve a large avoided burden per unit of mass, as well as keep (critical) raw materials within the (European) economic system. 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).

These aspects call for detailed data to be collected on two levels. On the micro-level, material composition data for all components of the WEEE and on the efficiency of the recycling operations should be established. Furthermore, to comply with the targets from the WEEE directive, data on the macro-level, quantifying the amount of WEEE that is generated and collected nationally, should be available. Combining these two levels allows estimating the total valorized resource potential of the waste stream in a country.

In this paper, the performance of the WEEE recycling chain in Belgium is assessed. As IT equipment is especially rich in valuable and critical materials (such as platinum group metals (Cui and Zhang, 2008) and rare earth elements (Binnemans et al., 2013)), the recycling of a desktop and a laptop computer, as carried out in 2013, is selected as a case. The assessment is performed in four steps. First, the recycling is analyzed through material flow analysis (MFA) at the level of specific materials to obtain an overview of the flows. Second, an indicator is calculated, which quantifies the effectively recycled weight ratios of these specific materials, which is linked with the WEEE Directive targets. Third, a second indicator expresses the recycling efficiency in terms of recovery of critical raw materials, in order to address the current strong policy focus on these materials. Finally, to go beyond the simple mass-based focus, the natural resource consumption of the recycling scheme in a life cycle perspective is calculated and benchmarked with a non-recycling scenario. The non-recycling scenario consists of landfilling the waste flow under study and the supply of the very same Basket of Products (BoP) offered by the recycling scheme, but starting from primary natural resources. The natural resource savings in a life cycle perspective are accounted for by the Cumulative Exergy Extraction from the Natural Environment method (CEENE), which quantifies the natural resource consumption in thermodynamic units.

## 2. Materials and methods

### 2.1. Description of the recycling chain

The WEEE recycling chain generally comprises three major steps: collection and sorting, dismantling and mechanical separation (primary treatment), and end-processing (see Fig. 1). Information on the two first steps in the chain was gathered in collaboration with Recupel and Galloo respectively.

In the first step, the discarded electrical and electronic appliances are collected and sorted. In Belgium, this is managed by the producer responsibility organization Recupel. Collected WEEE is first checked, and equipment that can be reused 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 latter OVE fraction (Huisman and Baldé, 2013; Els Verberckmoes, Recupel Treatment Manager, personal communication).

The contribution of reuse to resource savings can be either positive or negative. The efficient reuse of discarded products can contribute to significant resource savings when replacing the

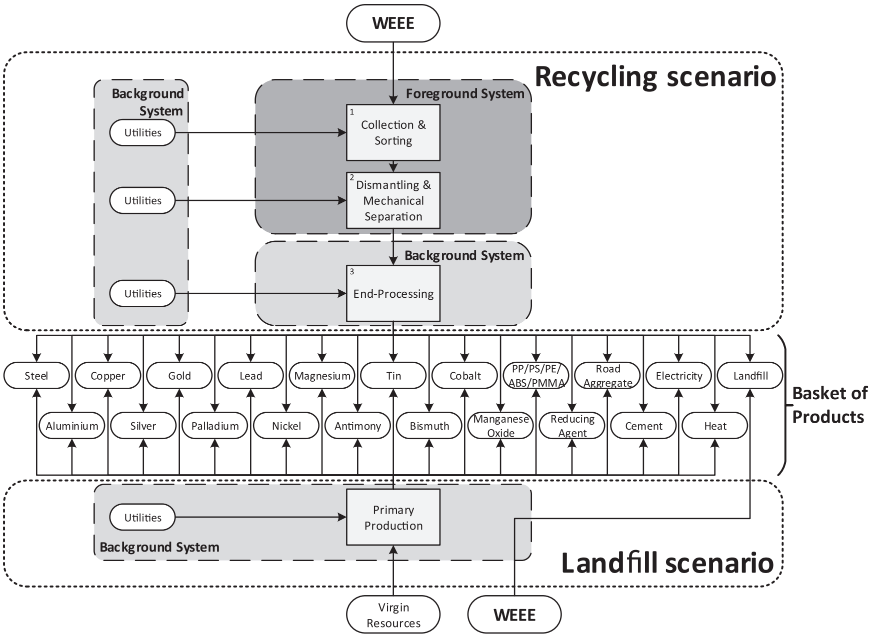


**Fig. 1.** Overview of the recycling chain and presentation of the system boundaries. The recycling scenario provides a Basket of Products (BoP) from secondary resources and is benchmarked with a landfill scenario where the waste is landfilled and where the BoP is to be provided from virgin resources through primary production.

purchase of a new product, and thus there is value in reusing devices which are in a good condition and have a broad resale market. However, reusing older equipment can delay the introduction of new, more (energy) efficient products, and in a rapidly evolving market with increased versatility and improved functionality, the performance of old equipment is not always guaranteed. Therefore, the reuse potential of WEEE discarded by consumers has been relatively limited. Furthermore, reusing these products in regions with a lower performance standard, but also with a weaker recycling infrastructure, can even prevent resource savings after the use phase because of a lack of proper treatment (Chancerel, 2010; Sahni et al., 2010). All in all, Truttmann and Rechberger (2006) showed that the effect of efficient collection and recycling on the achieved resource savings is much higher compared to reuse, as all products should ultimately end up in a recycling system. This study therefore focuses on assessing the performance of the recycling chain itself, and it is assumed that devices reaching the recycling system have no efficient reusability.

As Recupel was not able to provide the distance covered by the collection transport, an estimation 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 used, consisting for 15% of light-duty transport, and for 85% of heavy-duty transport.

The second step is the primary treatment, where the devices are dismantled and the materials are separated mechanically, to further treat them separately. This step is crucial in the overall recycling chain, as it determines the extent to which the materials are guided to the appropriate end-processing step for recycling (Chancerel et al., 2009). In this study, the treatment process at Galloo in Menen (Belgium) was therefore thoroughly analyzed, which is a very relevant case for Belgium, as almost half of the OVE fraction collected in Belgium is treated here.

This treatment process at Galloo starts with the manual dismantling of the personal computer (PC) towers, laptops and cathode ray tube (CRT) screens, 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. The other dismantled components are further treated in-house, as well as the flat panel display (FPD) screens, mice and keyboards, to additionally separate the materials they are made of, before being delivered to the end-processing step. These further treatment operations include shredding, and the use of among others magnetic and eddy current separators. The utilities used in the primary treatment process include electricity (provided by an anaerobic digestion plant), chemicals to facilitate the density separation and the binding of hazardous substances, gasoline, and internal transport (Luc Waignein, Group Galloo Chief Research & Development Officer, personal communication).

The final step is the end-processing, which is carried out to produce secondary raw materials which form the BoP from the fractions that leave the primary treatment plant. First of all, scrap of iron and steel, aluminium, magnesium, copper, as well as fractions rich in non-ferrous metals such as PCBs, are sent to the respective smelters. Next, five plastic polymers are separated (polypropylene (PP), polystyrene (PS), polyethylene (PE), acrylonitrile butadiene styrene (ABS) and poly(methyl methacrylate) (PMMA)) and processed to secondary plastic pellets. Laptop batteries are recycled, and 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. Button cell batteries are assumed to be landfilled due to lack of information.

Non-material recovery processes take place 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 cement to replace regular Portland cement (Kellenberger et al., 2007; Siddique et al., 2011). Similarly, organic impurities in smelters act as an additional reducing agent and fuel, thus replacing cokes (Schlüp et al., 2009). Finally, mineral fractions are used as a construction material, thus replacing gravel from mines. These processes are referred to as downcycling, as the materials are converted to products with reduced functionality. Additionally, organic waste fractions are incinerated with electricity and heat recovery. The transport activities from Galloo to the end-processing facility are also taken into account, and these are mainly performed using road transport, as well as some naval transport.

To benchmark the recycling scenario, Fig. 1 represents a landfilling scenario where WEEE is landfilled and where the BoP offered by the recycling starting from waste (secondary resources) is to be delivered by primary production using virgin resources.

## 2.2. Scope

### 2.2.1. Functional unit

The functional unit used in this study is a unitary functional unit (reference flow, Laurent et al., 2014), corresponding to the treatment of one tonne (1000 kg) of desktop PCs with peripherals (referred to as ‘desktops’ further on). 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, and in the other cases a ball mouse. Similarly, also a ratio for the screen type is used, calculated as the amount of CRT screens to 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 of laptop computers is considered as well, and here no peripherals are taken into account, so the power charger is neglected.

### 2.2.2. System boundaries

The system boundaries, together with the two waste treatment scenarios considered, are presented in Fig. 1. In this study all recycling steps after the product has been brought to a collector by the user are included. The first two steps of the recycling chain (collection and primary treatment) are included in the foreground system, as primary data was used to model these operations. The final step (i.e. the end processing step that produces secondary materials), the production processes of all the utilities used in the foreground system, as well as the total landfill scenario, are in the background system. The quantitative information for the background system was modelled using the Ecoinvent v.2.2 database (Ecoinvent Centre, 2010).

## 2.3. 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 (Brunner and Rechberger, 2004).

In this study, an MFA is performed on the primary treatment plant and the various end-processing facilities, in order to determine the material flows through the WEEE recycling chain. As mentioned in Section 2.1, 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 desktops and 20 tonnes of laptops) was provided. For each manually separated component, a material composition from various literature and other sources was used to establish the total material input into the process (Chancerel and Rotter, 2009; Peter Debaere, Galloo Menen WEEE coordinator, personal communication; Fisher et al., 2006; Gmünder, 2007; Hikwama, 2005; Hischier et al., 2007; Huisman et al., 2008; Kahhat et al., 2011; Lee et al., 2004; Nnorom et al., 2011; RepTool, 2013; Shenzen Euni Battery co., 2013; Socolof et al., 2001; Umicore., 2013; von Geibler et al., 2003). Components present in both desktops and laptops, such as hard disks, 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: ferrous metals, aluminium, copper, precious metals (Ag, Au, Pd), other non-ferrous metals (Pb, Ni, Mg, Sb, Cr, Sn, Zn, Bi, Co, Ba, Hg), various plastic polymers, other organics (such as rubber and liquid crystals in LCD screens), minerals and others ($Sb_2O_3$, Si, $MnO_2$, Li, Ar, Ne, and unspecified fractions). The recycling of these materials then delivers the BoP shown in Fig. 1.

Next, the composition of the output streams from Galloo was determined. Mass data on the fractions manually dismantled were provided, as well as the outputs of the treatment of the general OVE waste stream. These data were combined with detailed knowledge on the treatment process and expert judgement of people at the company. Finally, efficiencies on two unit separation processes (air table separator: 95% (expert judgement) and eddy current: 90% (Zhang et al., 1998)) and on the recovery of some metals when treated through shredding and mechanical separation (Ag: 12%; Au: 26%; Pd: 26%; Ni: 100%; Fe: 96%; Cu: 60%; Al: 86%; from Bigum et al., 2012) were used as well. The same separation efficiencies as for gold and palladium are assumed for the metals present on PCBs for which no efficiency was available (Cr, Pb, Sb, Sn, and Zn). All this information is then combined to determine the path of the input materials through the process.

Average weights for the devices under consideration (see Section 2.2.1) were used: 12.33 kg for the desktop PC tower and 2.84 kg for the laptop (Chancerel and Rotter, 2009), 14.65 kg for the CRT screen and 5.28 kg for the FPD screen (Huisman et al., 2008), 1.18 kg for the keyboard and 0.12 kg for the optical mouse (Hischier et al., 2007), and 0.13 kg for the ball mouse (Hikwama, 2005).

The end-processing step was modelled using recovery efficiencies, 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%.

### 2.4. Material weight recycling indicator

The material weight recycling (MWR) indicator, proposed by Nelen et al. (2014a), expresses the weight of the materials that are effectively recycled at process level, in relation to the weight in the input, and is presented in Eq. (1). This means that only materials which are recycled to products similar to the original application are considered. This is in contrast to the way this is defined in the WEEE Directive, where all materials entering the recycling facility (so without taking losses into account, and also those without material recycling, such as ferrous metals in slags used as a construction material) count towards the recycling targets. The indicator thus determines the extent of effective entry of recycled materials into the secondary raw materials market.

$$\text{MWR} = \frac{\sum_{i=1}^{m} W'_i}{\sum_{j=1}^{n} W_j} * 100\,(\%) \tag{1}$$

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 resulting 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.

### 2.5. Market analysis

Quantitative information on the total WEEE amount generated is usually unavailable. As the collection targets set by the EU from 2016 onwards will be based either on the volume EEE put on the market, or on the WEEE generated (see Section 1), 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 approach from Wang et al. (2013) is used, and the product sales are first of all estimated using the Eurostat database (Eurostat, 2015), with the average weight from Section 2.3 used to convert the number of pieces to mass. As the quality of the statistics for the desktops was deemed to be too low, only laptops will be taken into account for the market analysis. Next, the product lifespans are used to estimate the lifetime of the product before it becomes waste. This discard-based lifespan profile is modelled using the Weibull distribution function, presented in Eq. (2):

$$L^{(p)}(t,n) = \frac{\alpha(t)}{\beta(t)^{\alpha(t)}}(n-t)^{\alpha(t)-1} e^{-[(n-t)/(\beta(t))]^{\alpha(t)}} \tag{2}$$

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 year $t$, 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 $n$ using Eq. (3):

$$W(n) = \sum_{t=t_0}^{n} \text{POM}(t) \cdot L^{(p)}(t,n) \tag{3}$$

### 2.6. Recycled material criticality indicator

As mentioned in Section 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), presented in Eq. (4), was proposed by Nelen et al. (2014a). This indicator is the same as the MWR-indicator, with additional criticality weighting factors.

$$\text{RMC} = \frac{\sum_{i=1}^{m} W'_i \cdot \text{EI}_i \cdot \text{SR}_i}{\sum_{j=1}^{n} W_j \cdot \text{EI}_j \cdot \text{SR}_j} * 100\,(\%) \tag{4}$$

With:

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

The economic importance and supply risks in Eq. (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.

### *2.7. Quantification of natural resource consumption and savings by 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, according to the standards by the International Organization for Standardization (2006). In this study, the focus lies on natural resource consumption in function of the Area of Protection (AoP) Natural Resources, as recycling should be an approach that helps in saving natural resources at the cradle, besides preventing environmental and health damage. Here, the natural resource consumption at the cradle is expressed in Cumulative Exergy Extraction from the Natural Environment (CEENE) and quantifies the used natural resources (in megajoules exergy, $MJ_{ex}$), in eight 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).

The Ecoinvent database is used to model the processes of the background system (Ecoinvent Centre, 2010). However, 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). Moreover, 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. Results and discussion

### *3.1. Material flow analysis*

The overall results of the material flow analysis of the primary treatment plant are presented in Fig. 2. This figure shows the material composition of the input (from the literature sources mentioned in Section 2.3), as well as the total material flows to the end-processing stage. These flows are shown in Figs. 3 and 4 separately for each material category, for desktops and laptops respectively. Tables underlying these results on a mass basis are supplied in the Supplementary data (Appendix A).

For desktops, Fig. 2 shows that the main mass 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 minerals recycler, which reflects the major input materials. In the case of laptops, this is more evenly distributed.

From Figs. 3 and 4, it is clear that there is not a large potential for extra recycling of ferrous metals from desktops and laptops, and the same goes for aluminium. This is not the case for the other materials. When PCBs are shredded, a portion of the materials is lost to dust fractions, which are landfilled. This is especially true for precious metals. The recycling of these metals could thus be improved through a more advanced pre-treatment step, to manually extract and separate even more PCBs and send them to proper treatment (as suggested by Chancerel et al., 2009). Here, the added economic cost should then be compared to the achieved extra economic and environmental gains. For laptops, a large fraction of the plastics is landfilled. This is the result of the ABS/PC plastics present in the housing, which are not separated for recycling due to the high

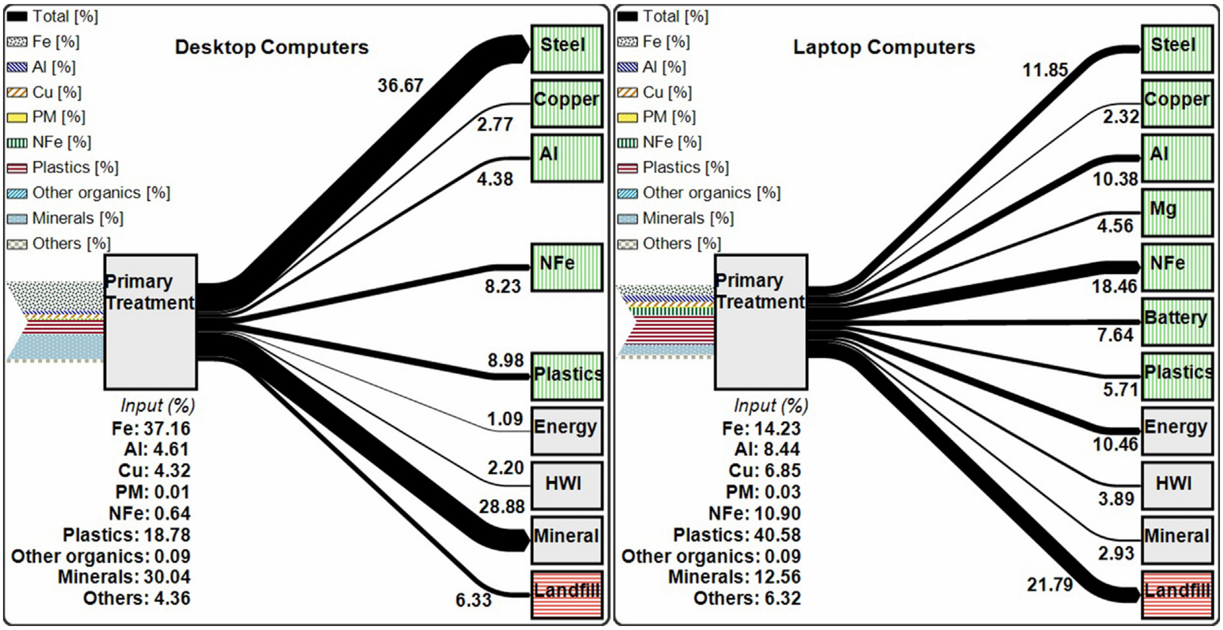
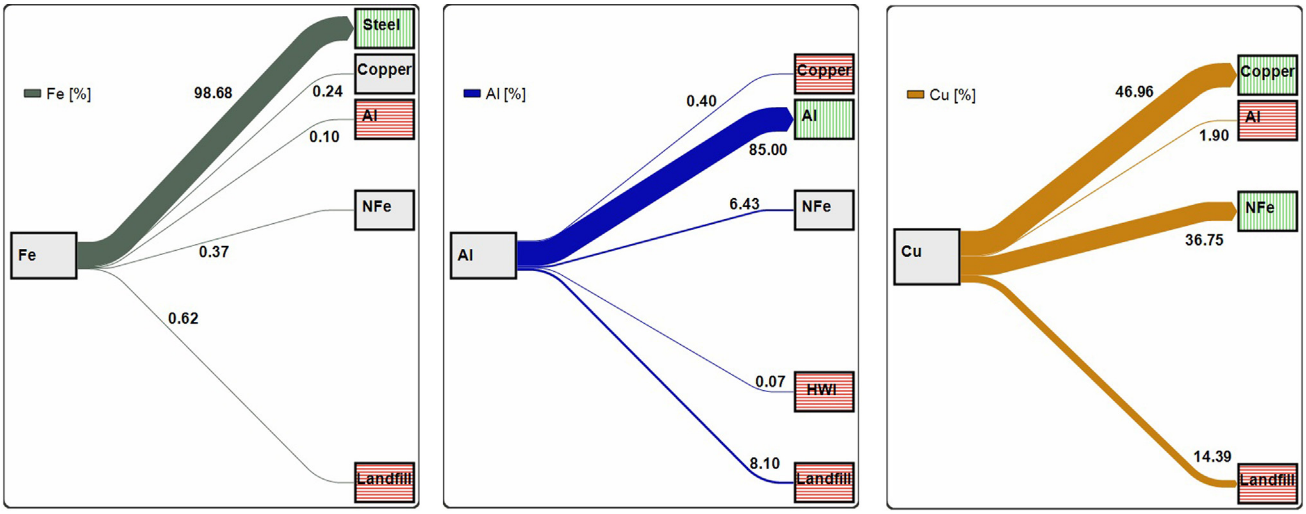
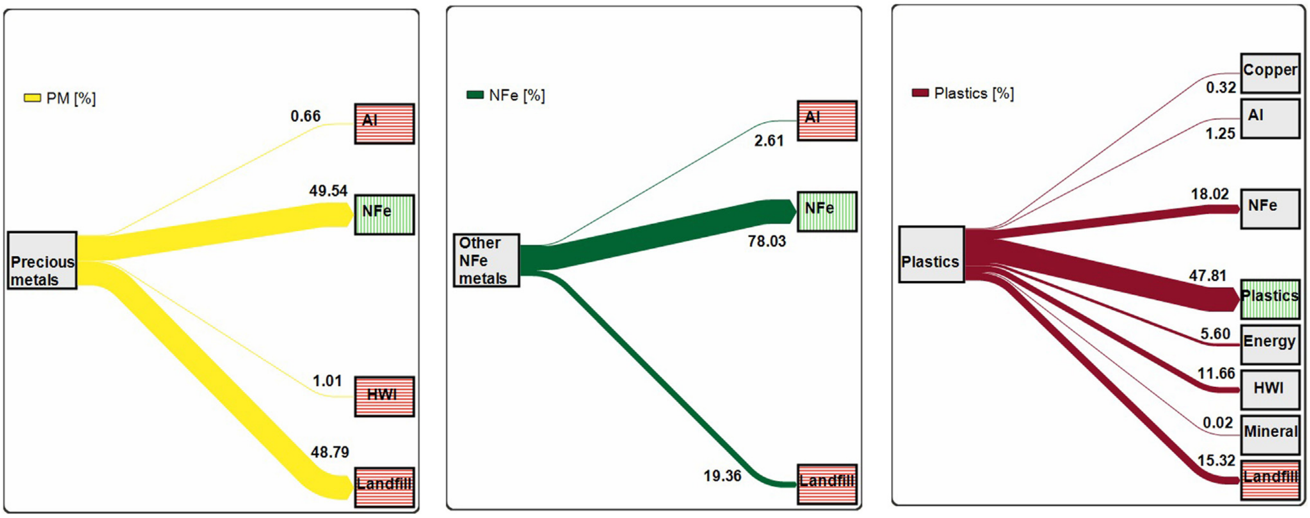


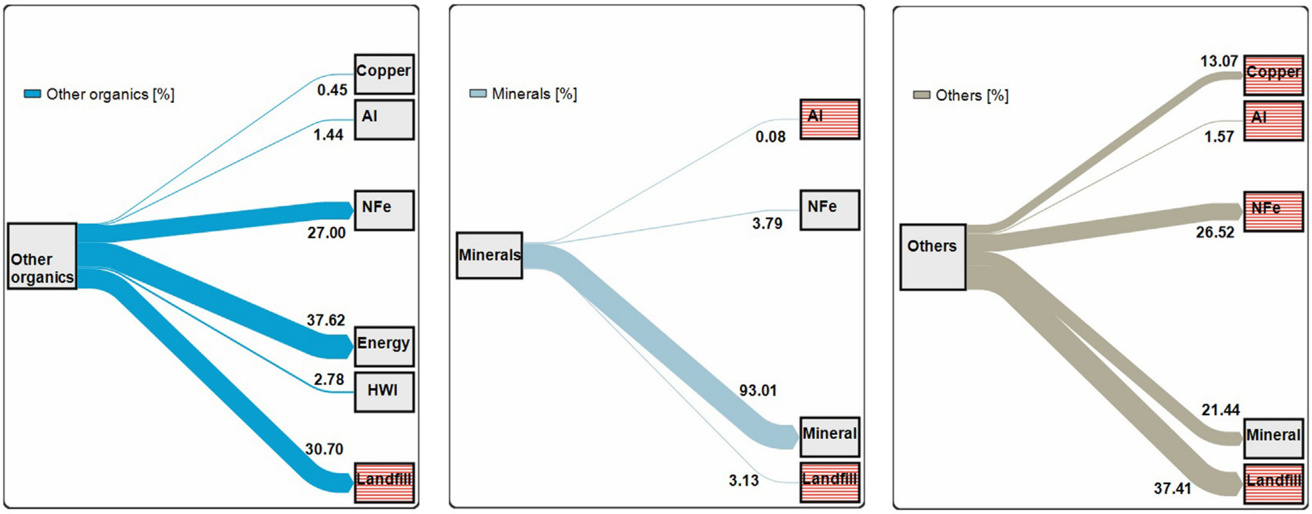
**Fig. 2.** Input of each material category of the end-of-life product and distribution to the end-processing stage, in mass percent. Destinations marked with green vertical lines indicate material recycling, grey other recovery processes (e.g. energy recovery or downcycling), and red horizontal lines disposal without any recovery. Steel: steel production; Copper: copper production; Al: aluminium production; Mg: magnesium production; NFe: non-ferrous metals production; Battery: battery recycler; Plastics: plastics production; Energy: energy recovery; HWI: hazardous waste incinerator; Mineral: minerals recovery; Landfill: landfill deposition.



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

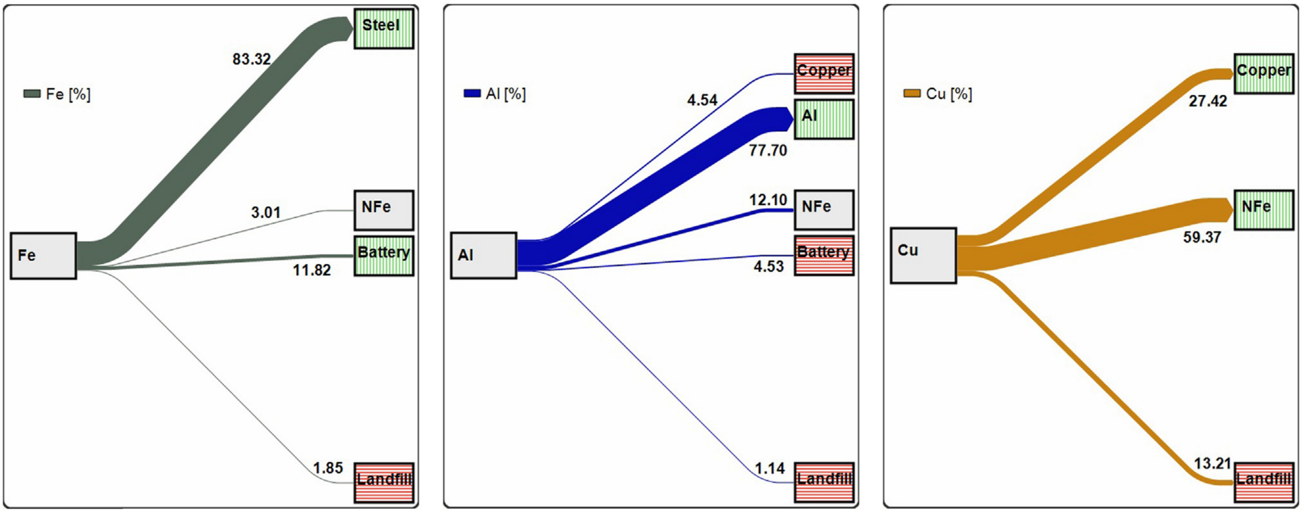


**(d)** Precious metals **(e)** Other non-ferrous metals **(f)** Plastics



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

**Fig. 3.** Distribution of the different material categories at the primary treatment step to the end-processing stage, for desktop computers with peripherals, in mass percent. Destinations marked with green vertical lines indicate material recycling, grey other recovery processes (e.g. energy recovery or downcycling), and red horizontal lines disposal without any recovery. Steel: steel production; Copper: copper production; Al: aluminium production; NFe: non-ferrous metals production; Plastics: plastics production; Energy: energy recovery; HWI: hazardous waste incinerator; Mineral: minerals recovery; Landfill: landfill deposition.



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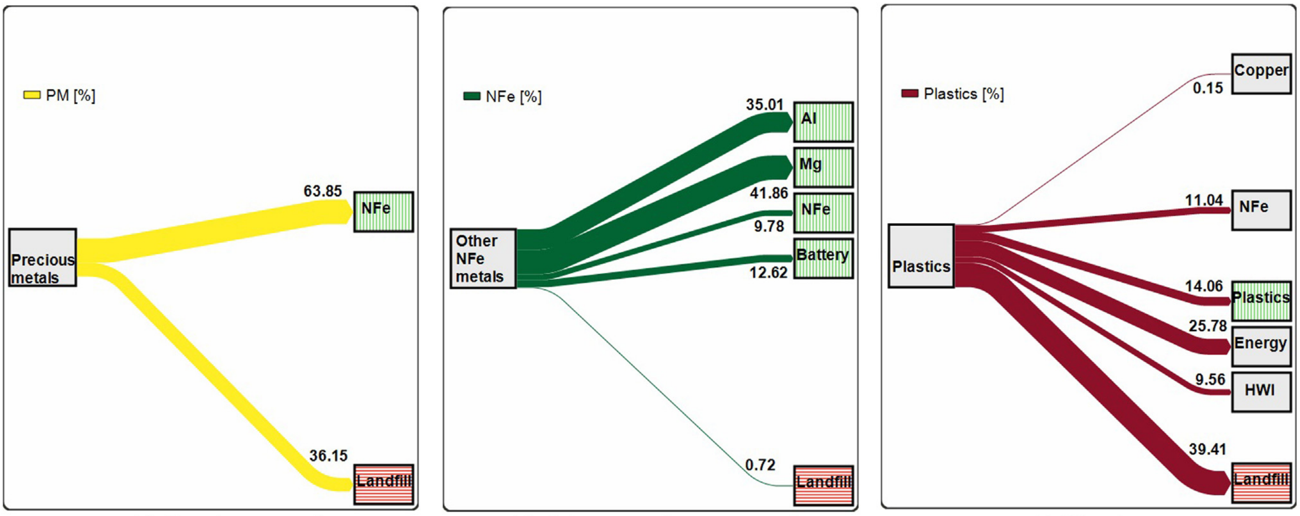
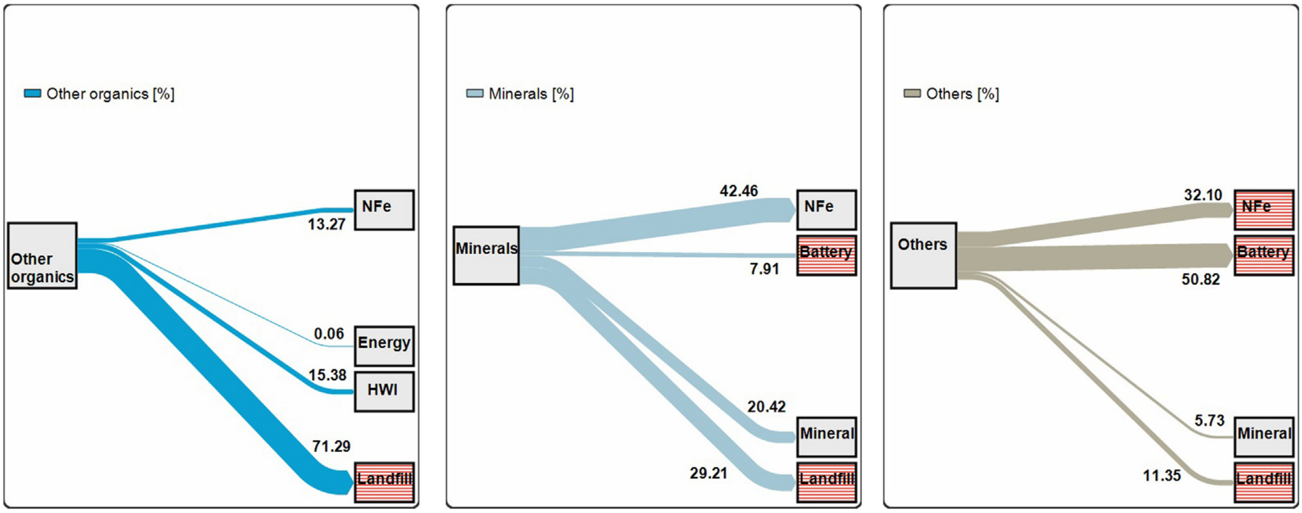


**(d)** Precious metals **(e)** Other non-ferrous metals **(f)** Plastics



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

**Fig. 4.** Distribution of the different material categories at the primary treatment step to the end-processing stage, for laptop computers, in mass percent. Destinations marked with green vertical lines indicate material recycling, grey other recovery processes (e.g. energy recovery or downcycling), and red horizontal lines disposal without any recovery. Steel: steel production; Copper: copper production; Al: aluminium production; Mg: magnesium production; NFe: non-ferrous metals production; Battery: battery recycler; Plastics: plastics production; Energy: energy recovery; HWI: hazardous waste incinerator; Mineral: minerals recovery; Landfill: landfill deposition.

**Table 1**
Effective material recycling per 1000 kg desktops and laptops treated, and the material weight recycling (MWR) indicator.

| | Desktop | | | Laptop | | |
|---|---|---|---|---|---|---|
| | Input, kg | Recycled, kg | MWR, % | Input, kg | Recycled, kg | MWR, % |
| Ferrous | $3.72 \times 10^2$ | $3.32 \times 10^2$ | 89 | $1.42 \times 10^2$ | $1.22 \times 10^2$ | 86 |
| Aluminium | $4.61 \times 10^1$ | $3.80 \times 10^1$ | 83 | $8.44 \times 10^1$ | $6.37 \times 10^1$ | 75 |
| Copper | $4.32 \times 10^1$ | $3.37 \times 10^1$ | 78 | $6.85 \times 10^1$ | $5.84 \times 10^1$ | 85 |
| Precious metals | $1.13 \times 10^{-1}$ | $5.52 \times 10^{-2}$ | 49 | $2.90 \times 10^{-1}$ | $1.84 \times 10^{-1}$ | 63 |
| Other non-ferrous metals | $6.39 \times 10^0$ | $1.87 \times 10^0$ | 29 | $1.09 \times 10^2$ | $9.82 \times 10^1$ | 90 |
| Plastics | $1.88 \times 10^2$ | $8.09 \times 10^1$ | 43 | $4.06 \times 10^2$ | $5.14 \times 10^1$ | 13 |
| Other organics | $9.14 \times 10^{-1}$ | 0 | 0 | $8.74 \times 10^{-1}$ | 0 | 0 |
| Minerals | $3.00 \times 10^2$ | 0 | 0 | $1.26 \times 10^2$ | 0 | 0 |
| Others | $4.36 \times 10^1$ | 0 | 0 | $6.32 \times 10^1$ | 0 | 0 |
| Total | $1.00 \times 10^3$ | $4.86 \times 10^2$ | 49 | $1.00 \times 10^3$ | $3.94 \times 10^2$ | 39 |

density of this copolymer, and thus partly end up in fractions to be landfilled.

### 3.2. *Material weight recycling indicators for the specific materials*

The amount of materials effectively recycled by the recycling chain (taking into account the recycling efficiencies at the end-processing step) of desktops and laptops is presented in Table 1. In this table, the MWR-indicator is calculated for each material separately, and for the total waste stream.

This shows that 49% of the materials in desktops and 39% of the materials in laptops are effectively recycled to form secondary raw materials. These rather low numbers, which should not be benchmarked to the WEEE Directive targets (as explained in Section 2.4), are caused partly by the low recycling rates for plastics. There are many different polymers present in the waste stream, and effective separation is challenging (Hopewell et al., 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 considered end-processing treatments are taken into account, the MWR-indicator increases to 87% for desktops and 85% for laptops.

### 3.3. *Resource potential of IT waste at national scale*

The results of the micro-level material flow analysis can now be coupled with a macro-level market analysis for Belgium to determine the resource potential of waste desktop and laptop computers in the country, when extrapolating the process at Galloo. Due to data constraints for the total waste estimation, the resource potential analysis will only include laptops.

In 2013, Recupel collected $37.8 \times 10^3$ tonnes of the OVE-fraction, which includes laptops. According to Galloo, these laptops constitute 0.7% of their incoming OVE-stream, resulting in 265 tonnes waste laptops collected by Recupel. The resources recycled from the total collected waste laptop stream in 2013 can thus be estimated to 32 tonnes of steel, 17 tonnes of aluminium, 15 tonnes of copper, 14 tonnes of plastics, and 48 kg of precious metals. These outputs might be of minor importance compared to the total national consumption as only one product is considered, but recycling the total WEEE stream could yield significant volumes of materials.

Based on Galloo's knowledge of destinations of its output flows, it can be determined that these secondary materials are produced for 19% (by mass) 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 contribute in making the EU more resource efficient and less dependent on imports for raw materials.

The previous conclusions are based on laptops that are actually collected by Recupel. On the other hand, the collection stage is a bottleneck in the recycling system, and a significant amount of devices never reaches the recycling chain. To estimate the total generated amount of waste laptops, the method described in Section 2.5 is used. For the parameters in Eq. (2), the values are taken from a Dutch case study (Wang, 2014; Wang et al., 2013), and are assumed to be valid for Belgium. Using Eq. (3), the size of the waste stream in 2013 can now be estimated, resulting in 2449 tonnes waste laptops. This is a slight underestimation, as laptops put on the market before 2007 were not yet included in the Eurostat data statistics. It thus follows that 11% of the waste laptops generated in 2013 were collected by Recupel.

It must be mentioned though that this result possibly has a large uncertainty, and that different predictions exist. For instance, a 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 11% for laptops only. This can be explained 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 official collection 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 to be disposed of in normal household waste (Bisschop, 2012; Hagelüken and Meskers, 2008; Kang and Schoenung, 2005). To meet the increased collection targets of the new WEEE directive (45% of all EEE put on the market, from 2016 onwards, see Section 1), additional efforts will have to be made. An increased collection of laptop computers should then improve the results presented in this section.

### 3.4. *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 criticality-based recovery efficiency from the recycling of the assessed raw materials.

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 by Nelen et al. (2014a) used in this study. 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 can lead 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 calculated 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).

### 3.5. *Life cycle assessment: natural resource consumption and savings*

#### 3.5.1. *Natural resource consumption of the recycling chain*

As the focus of this study lies on raw materials consumption, the impact on the AoP Natural Resources is considered and quantified by the CEENE method. The natural resource consumption of the recycling scheme in function of its consecutive steps, i.e. collection, primary treatment and end-processing, is presented in Fig. 5. It is clear from this figure that for desktops and laptops, the end-processing step has by far the biggest CEENE impact, compared to the impact of the collection and primary treatment steps.

The impact of the collection step is caused only by transport activities, as the receptacles for the 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 one for this step.

Other scenarios for the transport distance can be investigated as well, as this distance is based on an estimation, mentioned in Section 2.1. 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.

The biggest impact for the primary treatment step is caused by the use of chemicals (used for density separation and as a binding agent, around 73% for desktops and 68% for laptops), which causes mainly fossil fuels and metal ores consumption. For laptops, the disposal operations of waste fractions from the process also have a significant impact (around 23%), mainly because the housing of a laptop has a higher plastics share (see Fig. 2), part of which is lost in a waste stream in the main OVE treatment system.

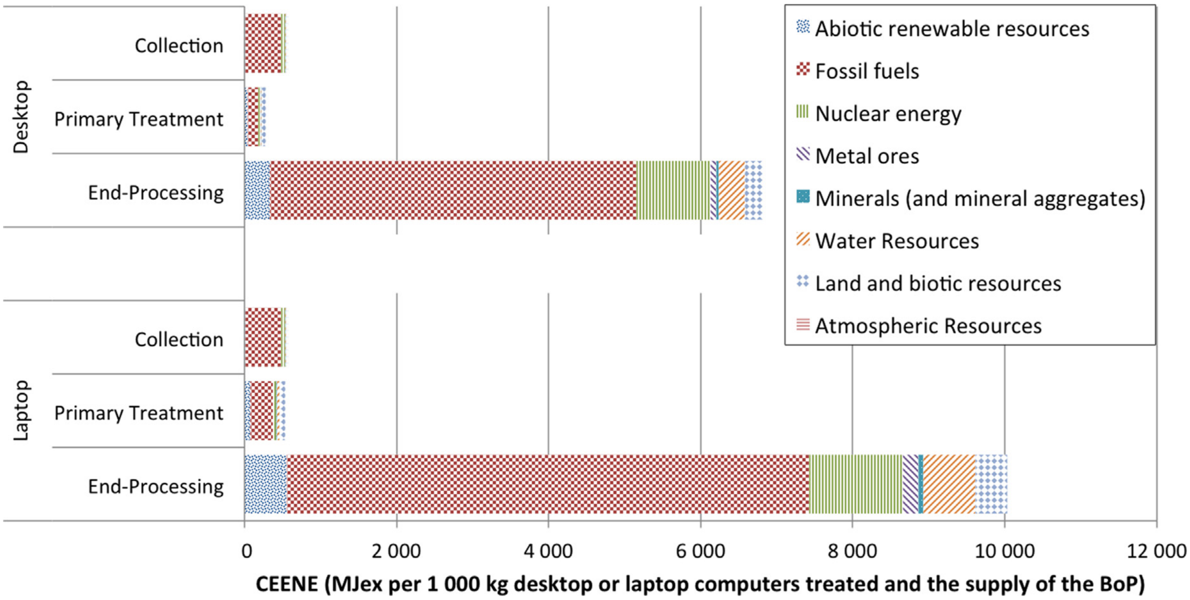


**Fig. 5.** Results of the CEENE analysis for the recycling chain of desktops and laptops, per treatment step.

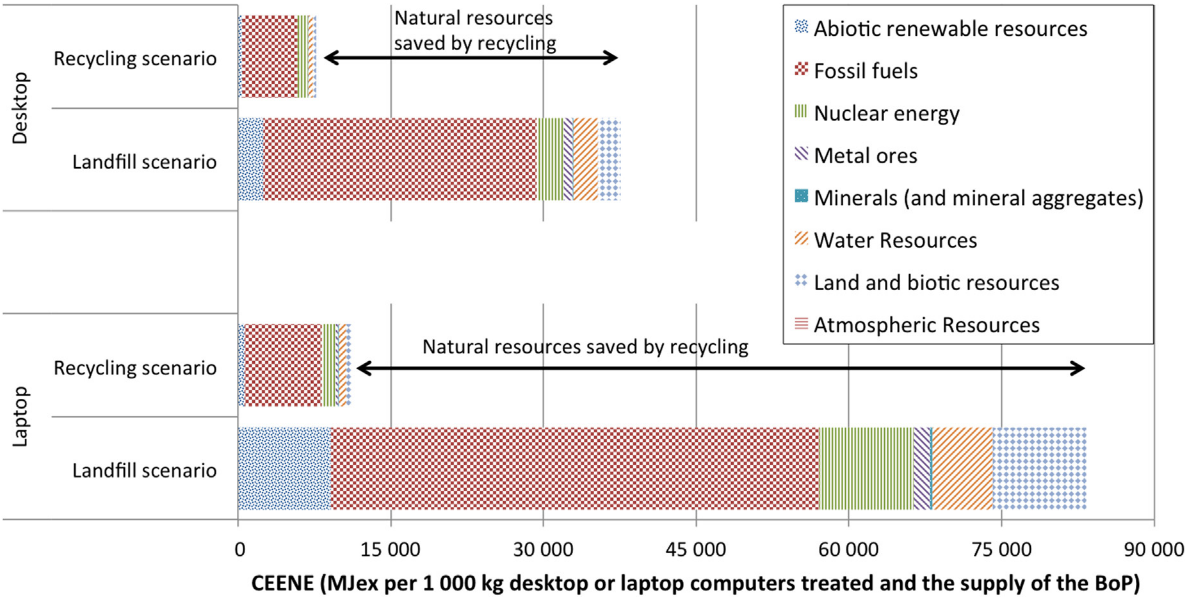


**Fig. 6.** Comparison of the CEENE analysis for the recycling and landfill scenario.

Looking at the impacts of end-processing, it can be observed, first for desktops, that they are caused mostly by the production of secondary steel (around 42%), because of the large steel content of the appliances. Transport to the end-processing facility is responsible for the second largest share (around 19%). Finally, secondary aluminium and copper production are responsible for the remaining major impacts (around 13% and 9% respectively).

Second, for laptops the impacts are more evenly distributed. The main share comes from 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 added there. 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 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. Finally, the production of secondary plastic pellets and secondary gold amount to 7% and 5% respectively. Overall, these impacts are mainly caused by fossil fuels consumption, because of the high energy needs of the smelting processes.

### *3.5.2. Natural resource savings by the recycling chain compared to the landfill scenario*

As mentioned in Section 1, the natural resource consumption in the landfill scenario consists of the landfill disposal activity itself, but also and mainly of the manufacturing of the BoP starting from virgin resources.

For desktops, 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 in impact 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 (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 almost negligible (around 2%).

In the case of laptops, 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 share of aluminium is important (around 26%), as well as the one of magnesium (around 16%). The plastic PMMA 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 desktops and laptops is shown in Fig. 6. The BoP of the recycling scenario is thus completely produced by the recycling activities. It is clear, for desktops as well as for laptops, 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 laptops. This is because these devices are smaller and more compact due to miniaturization of the appliances, resulting in a larger concentration of valuable resources. The recycling of these appliances therefore has a larger impact, compared to the one for desktops, but this scenario also achieves a much larger avoided burden. So although in the case of laptops a smaller percentage of the materials is recycled (see Section 3.2), the avoided burden achieved through this recycling is higher. This result again questions the relevance of setting recovery targets (e.g. in the WEEE Directive) that are only weight-based.

It can therefore 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 natural resources, while for the latter this is 87%.

## 4. Conclusion

In this study, the recycling of desktop computers with peripherals and laptop computers was assessed with different methods. 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 a more advanced manual dismantling step, although the resulting extra environmental and economic benefits have to be weighed up against the increased economic costs.

For desktop computers, 49% of all materials and 87% of metals, of which the recycling is possible at the considered end-processing facilities, are effectively recycled. For laptops, these values are 39% and 85%, respectively. The 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% of the critical mass is recovered, while for laptops this is 89%, 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 recycling of laptops in Belgium in 2013 achieved 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.

The natural resource consumption of the recycling chain at life cycle level was assessed as well, and compared with the landfilling scenario to quantify the natural resource savings owing to recycling. The consumption and savings were expressed in CEENE (Cumulative Exergy Extraction from the Natural Environment), which determines the (savings in) natural resource footprint by product recycling. 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 natural resource demand, compared to the collection and primary treatment. These end-processing demands 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.

Nevertheless, the natural resource consumption in the recycling scheme is much smaller than in a landfilling scenario, where materials have to be generated from virgin natural resources. Overall, recycling saves 80 and 87% of the natural resources in the case of desktops and laptops respectively. For desktops, the impacts of the landfill scenario are mainly caused by the primary production of steel, aluminium, gold, and ABS, while for laptops, the primary production of gold and aluminium are the most important impacts.

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 bottom-up analyses of product material compositions also focusing on the smaller material fractions are needed to increase the accuracy of the results, as the material composition has a large influence on the achieved benefits, and detailed composition data of EEE are not readily available. This is highlighted by the comparison with a previous study carried out in Belgium on the recycling of the wider product category IT equipment (Nelen et al., 2014b), where a general top-down material composition for the whole product group from Huisman et al. (2008) was used, which resulted in significant differences in the outcomes. This can also help to better determine the resource potential of waste appliances in Belgium. Consequently, better data on the generation of WEEE, and on the waste streams that are not collected (89% of the laptops according to this study), is needed as well, which will be crucial for reporting the achieved collection targets set by the EU.

## Conflict of interest

The authors declare no conflict of interest. The views expressed in this article are personal and do not necessarily reflect an official position of the European Commission.

## Acknowledgements

E.V.E. was supported financially by the Flemish Policy Research Centre for Sustainable Materials Management (Steunpunt SuMMa) for this research. Financial support from the European Commission (Expert Contract Number CCR.IES.C391493.X0) is acknowledged as well. The authors also wish to thank Els Verberckmoes from Recupel, Luc Waignein and Peter Debaere from Galloo, Dimitri Strybos from OVAM, Fabrice Mathieux and Laura Talens Peiró from JRC, and the anonymous reviewers for their valuable inputs.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2015.10.032.

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