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A multidimensional indicator set to assess the benefits of WEEE material recycling

Dirk Nelen [a,*], Saskia Manshoven [a], Jef R. Peeters [b], Paul Vanegas [b,c], Nele D'Haese [a], Karl Vrancken [a,d]

[a] VITO, 200 Boeretang, 2400 Mol, Belgium
[b] KU Leuven, Department of Mechanical Engineering, Centre for Industrial Management, Belgium
[c] University of Cuenca, Ecuador
[d] University of Antwerp, Department of Bio-engineering, Belgium

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ABSTRACT

EU strategies for waste management have long recognized the key role of recycling to move towards sustainable consumption and production. This resulted in a range of regulatory measures, among which the Waste Electrical and Electronic Equipment (WEEE) directive, which sets weight-based targets for recovery, preparation for re-use and recycling. The increasing strategic relevance of the supply of raw materials has, however, spurred a more integrated approach towards resource efficiency. In addition to the prevention of disposal, recycling practices are now also meant to contribute to sustainable materials management by pursuing (i) a higher degree of material cycle closure, (ii) an improved recovery of strategically relevant materials, and (iii) the avoidance of environmental burdens associated with the extraction and refining of primary raw materials. In response to this evolution, this paper reports about the development of an indicator set that allows to quantitatively demonstrate these recycling benefits, hence going further than the weight-based objectives employed in the WEEE directive. The indicators can be calculated for WEEE recycling processes for which information is available on both input and output fractions. It offers a comprehensive framework that aims to support decision making processes on product design, to identify opportunities for the optimization of WEEE End-of-Life scenarios, and to assess the achieved (or expected) results of implemented (or planned) recycling optimization strategies. The paper is illustrated by a case study on the recycling of LCD televisions.

1. Introduction

For decades, waste management strategies have recognized the key role of recycling to move towards sustainable consumption and production. As a result, European waste management policies are developed in line with the 'waste hierarchy', favoring the prevention of waste, followed by reuse, recycling, recovery and disposal (Commission of the European Communities, 1989). With respect to this hierarchy principle, the Fifth Environmental Action Programme was the first official policy mentioning Waste Electrical and Electronic Equipment (WEEE) as one of the target areas to be regulated (European Commission, 1992). Years later, this resulted in a first directive on the treatment of WEEE (European Parliament, 2003). This directive sets weight-based targets for collection, preparation for re-use, recycling and recovery as percentages of generic WEEE streams, providing an important driver for the development of WEEE collection and recycling schemes (Huisman et al., 2008; Padmanabhan, 2009; Wäger et al., 2011). A recast that followed in 2012 aimed to further increase the amount of e-waste that is appropriately treated (European Parliament, 2012).

However, traditional views on waste management have been changing recently. Since concerns are growing about our finite material reserves, more and more waste streams are regarded as valuable material sources (Cohen, 2007). The increasing strategic relevance of the supply of raw materials has spurred an integrated approach towards resource efficiency, giving rise, among other things, to the flagship initiative 'A resource efficient Europe' under the Europe 2020 Strategy (European Commission, 2011). This Initiative, together with the Raw Materials Initiative (Commission of the European Communities, 2008) stresses the importance of more effective and efficient recycling to secure future European supply.

* Corresponding author. Tel.: +32 16335924.
E-mail address: dirk.nelen@vito.be (D. Nelen).

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Hence, one of the critiques on the WEEE Directive is that there is no focus on the recovery of scarce resources (Friege, 2012), even though EEE contains a significant number of special and precious metals,[1] such as indium, silver and palladium, particularly in Printed Wiring Boards (PWB). As these elements are often present in low concentrations and contained in complex components difficult to access, their recovery is not easy and energy-intensive. Notwithstanding this barrier, these metals "*have significant relevance for clean- and high-tech applications, are valuable both from an economic and environmental perspective, and face specific supply challenges since they derive mostly from coupled production with other carrier metals*" (Hagelüken and Meskers, 2010). It is, therefore, unacceptable that a large proportion of precious and special metals present in WEEE is still lost in the recycling process (Chancerel et al., 2009). Weight-based recycling targets, such as the ones defined in the WEEE Directive, are not an incentive to overcome this problem.

Another important discussion point concerns the observation that these weight-based targets do not sufficiently contribute to an improvement of the environmental effectiveness of recycling processes (Huisman et al., 2008). Irrespective of these targets, a proper assessment of recycling performances should acknowledge the connection between the recycling of materials and the potential avoidance of environmental burdens associated with the extraction and refining of the respective raw materials. In contrast to their relative weight contributions, the environmental benefits that can be achieved by recycling precious and special metals, are often much larger than for bulk metals (Wäger, 2011). Huisman and Stevels (2006) demonstrated that, although recycling of the plastics in a cell phone would be favored from a weight-based perspective (since they make up about 50% of the device), the recovery of precious metals such as palladium and gold should be prioritized from an environmental point of view.

A third concern often mentioned, is whether a recycling definition should be based on individual materials or on the destinations of the output fractions from recycling operations, often containing a mix of materials. Due to the presence of pollutants and impurities, output fractions that are considered as successfully recycled will not always be a perfect substitute for the corresponding virgin materials. Avoiding this effect, referred to as 'downcycling', is essential in order to achieve material cycle closure. However, the dilemma between maximizing yield and maximizing purity always requires a compromise to be made.

In response to these criticisms on the recycling targets put forward in the WEEE Directive, efforts to improve and complement the assessment of recycling benefits are ongoing. An example of this is the identification of a basket of indicators to quantify environmental impacts of resource use such as the Environmentally weighted Material Consumption (EMC) (EEA, 2012). But despite these efforts, the European Environment Agency recognizes that there still is a lack of robust methodologies and operational indicators to measure and monitor the impacts related to resource use. Moreover, Gossart (2011) observes that the heterogeneity of paths that EU Member States have adopted to implement the WEEE Directive resulted, on the one hand, in the selection of different indicators to evaluate its success and, on the other hand, in different ways to construct indicators that assess similar sustainability attributes. He therefore proposes to develop a model-based approach to complement erratic data quality and a set of indicators, i.e. the E-waste Solutions Index (ESI), which allow to roughly compare countries. He concludes that "*it might be worthwhile developing a simple set of indicators that does have an impact on the policy process*".

In addition to this, the Institute for Environment and Sustainability (IES) of the European Commission Joint Research Centre (JRC) investigated the development of life-cycle based waste management indicators to quantify and monitor the potential environmental impacts associated with the management of a number of selected waste streams generated throughout Europe. One of the conclusions of this study was that such indicators would benefit from a higher disaggregation level of waste categories in waste statistics, more detailed information on waste composition and a higher number of waste streams (Manfredi and Goralczyk, 2013).

Finally, also the UNEP (2013) recently made some recommendations concerning the development of recycling indicators. According to this institute these should aim to guide decision makers, be product centric, be based on recycling physics and reflect the complexity of products. As can be noted, such approach goes further than simple mass flow analysis approaches, which "*ignore that recycling streams are a complex combination of materials, which cannot be separated by physical separation and hence drastically affect the quality of the streams*" (UNEP, 2013).

It can therefore be concluded that there is a need for simplified and robust operational indicators covering sustainability aspects related to WEEE recycling. E-waste treatment accomplishes two tasks: recover materials and control the potential for toxicity and emissions (Wang, 2014). In this article, a set of four indicators is proposed that allows to quantify recycling benefits related to the first of the tasks distinguished by Wang. They can be calculated when the material compositions of the input and output of a recycling process are known as well as the purity, market price and functionality of the output fractions. In order to minimize the inevitable gap between scientific preciseness and practical metrics, these material compositions should relate to a particular product, a product category or a product mix and should not be estimated based on a simple mass flow analysis. Obviously, the reliability of the results will improve by the use of adequate sampling and analysis procedures, recycling facility data and/or simulation tools. With regard to the latter, specific software tools that build on fuzzy set recycling (liberation) models are available (Reuter, 2011; Reuter and van Schaik, 2012).

The rest of this paper is organized as follows. The next section gives a brief overview of the chosen approach and the objectives that guided the selection of the indicator set. The third section elaborates on the theoretical background of each of the constituting indicators, presents the equations to quantify them and discusses their combination into a single recycling index. Subsequently, the indicators are applied to a case study on the recycling of LCD televisions. Finally, possible areas of application are identified.

2. Approach and objectives: from theoretical concepts to practical indicators

Plenty of indicators could be proposed to measure strategic aspects of material recovery (Cleveland and Stern, 1998; Huisman, 2003; Huisman and Stevels, 2006). The selection of indicators to capture a complex reality into a single number implies numerous simplifications and assumptions, linking them to a specific context. In relation to this study, this context was framed as one of sustainable materials management (SMM), defined by the OECD in 2005 as "*an approach to promote sustainable materials use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the life-cycle of materials, taking into account economic efficiency and social equity*".

[1] Precious metals are gold, silver, ruthenium, rhodium, palladium, osmium, iridium, and platinum; special metals refer here to antimony, bismuth, cobalt, gallium, germanium, indium, lithium, molybdenum, rare earth elements, rhenium, selenium, silicon, tantalum and tellurium.

Later on the OECD (2012) formulated four broad principles to guide governmental policies in the implementation and improvement of systems to sustainably manage materials. Recycling is seen as a key strategy to meet the first of these four principles, i.e. 'preserve natural capital', which refers to the overall basis for SMM. In order to widen the weight-based approach employed by the WEEE Directive, the four indicators presented in this paper make use of this preservation principle. They are called as follows:

a) Weight recovery of target material(s)
b) Recovery of scarce materials
c) Closure of material cycles
d) Avoided environmental burdens

These indicators, which will be elaborated on in the next section, aim to support the assessment of a recycling process' performance in a practical and quantitative way. Because SMM holds strategic advantages from the perspective of both environmental and commercial policies, and of private and public stakeholders, this will be done while reflecting on different strategic topics in European WEEE recycling, that is: (i) closing material cycles, (ii) recovering (strategically) relevant materials and (iii) avoiding environmental burdens associated with the extraction and refining of primary raw materials. The assessment results are therefore intended to support decision-making processes on product design, to identify opportunities for the optimization of WEEE End-of-Life scenarios and to assess the achieved (or expected) results of implemented (or planned) recycling optimization strategies.

As mentioned before, the goal of this study was to design indicators that can be calculated when the material compositions of the input and output fractions of a recycling process are known as well as the purity, market price and functionality of the output fractions. In the present article this recycling process is seen as a sequence of actions, constituting an environmentally and economically sound recycling process, starting from a given input of collected EoL-products offered at a recycling facility and ending with the marketing of the outputs (products, materials or substances). These outputs might be used for the original or for other purposes. This implies that system boundaries include dismantling, handpicking, shredding and sorting treatments as well as downstream processing of output fractions in order to obtain functional and applicable outputs (e.g. metallurgical treatment, purification, granulation, etc.).

3. Four indicators to assess WEEE recycling in a context of sustainable materials management

In this section, the choice for each of the proposed indicators is briefly motivated from a European WEEE recycling perspective. The implications of some simplifications that were necessary to make, are illustrated in the case study in the next section.

3.1. Weight recovery of target material(s) (I_W)

Although the selection of an indicator on weight recovery seems to be a quite unambiguous issue, it is observed that even weight-based recyclability definitions are subject to many different interpretations. For example, material recycling efficiencies could be based on the total amount of materials sent to secondary material processing, but also on the amount of target materials only (Huisman, 2003). Article 11 of the WEEE Directive recast states that "*the achievement of the targets shall be calculated, for each category, by dividing the weight of the WEEE that enters the recovery or recycling/preparing for re-use facility, after proper treatment in accordance with Article 8(2) with regard to recovery or recycling, by the weight of all separately collected WEEE for each category, expressed as a percentage*" (European Parliament, 2012). This means that the official WEEE recycling targets only take into account the WEEE that enters the recycling facility, without differentiating between more and less environmentally preferable options, between different levels of reapplication, or between the actual amounts and qualities of materials and material mixes that result from the recycling process (Huisman et al., 2008). According to this calculation method from the WEEE Directive, materials that are present as impurities in output fractions are also regarded as recycled weight.

Table 1
Overview of the indicator 'weight recovery of target material(s)'.

Indicator I_W	Recycled material weight
Equation	$I_W = \sum_{i=1}^{m} W_i' / \sum_{j=1}^{n} W_j$
m: number of output fractions from the recycling process, destined for material recovery	
n: number of materials present in the input of the recycling process	
W_i': weight of target material(s) in output fraction i	
W_j: weight of material j present in the input of the recycling process	
Numerator	Total weight of recycled target materials
Denominator	Total weight of the input of the recycling process
Rationale	The indicator equals 1 in the hypothetical situation that over the complete recycling chain all input materials are completely recovered in output fractions composed of only target materials and desired impurities.

This indeed may be true from the point of view of avoided weight that goes to landfill, but not when the reentry of recycled materials into a secondary raw material market is intended. Then, in most cases, the impurities should in fact be regarded as 'lost'; although in a few cases the presence of impurities might be beneficial for reapplication. For example, impurities of phosphorus or aluminum in recycled steel scrap might be advantageous for some steelmaking processes (Liu et al., 2007; Osawa et al., 2006). Only if this is the case, the corresponding impurities can be accounted for as truly recycled. In this context, the recycling Metal Wheel (Reuter and van Schaik, 2012) provides a fair insight into the fate of a series of metal alloys throughout metallurgic refining processes.

Based on this discussion, and in contrast to the calculation method of the WEEE directive, an indicator on effectively recovered weight is proposed that is calculated as the sum of the weights of the target materials in each recycled output fraction divided by the total material weight of the input (Table 1).

3.2. Recovery of scarce materials (I_S)

The mechanisms behind material scarcity, as well as the meaning and consequences of introducing such a concept, have been, since Malthus' essay on the Principle of Population (Malthus, 1798) subject to an intense debate. Numerous scarcity indicators have been proposed since. Cleveland and Stern argue that much of the debate about the strengths and weaknesses of such indicators ignores the fact that different indicators measure different types of scarcity. They propose the terms 'use scarcity' and 'exchange scarcity', in relation to the classical concepts of use and exchange value (Cleveland and Stern, 1998). A distinction can also be made between absolute and temporary scarcity, and between structural and technical scarcity (Hagelüken and Meskers, 2010). Other authors make a distinction between reserve based and price based mineral scarcity indicators (Koppelaar, 2011).

At European level, the Raw Materials Initiative determined the criticality for a list of 41 minerals and metals. The label 'critical' was given to materials "*when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw* *materials*" (European Commission, 2010). From a pragmatic point of view, three main aspects were included in the definition of criticality: the economic importance of the considered raw material, its supply risk and an environmental country risk. For calculating the supply risk, the political-economic stability of the producing countries, the level of concentration of production, the potential substitution and the recycling rate were taken into account. Geological availability was not considered as the time horizon of the study was only ten years. In addition to this, the environmental country risk, i.e. the potential of environmental measures restraining access to deposits or supply of raw materials, turned out not to have a significant impact. Hence, it was not included in the quantification either. Consequently, criticality values may vary over time as the supply risk for the EU and the economic importance of materials can change due to political perturbations and technological developments. This means that also new materials may be added to the current list, which is suggested to be updated every five years. Prins et al. (2011) concluded that such a list could help addressing key resource policy objectives if there would be appropriate indicators. Such indicators can be found in the work of Graedel et al. (2012), who broadened the methodology to determine a commodity's criticality with factors such as supply risks at different time scales and vulnerability to supply restrictions.

Finally, also the characterization factors given by some Life Cycle Impact Assessment (LCIA) methods might be useful as a scarcity indicator. Although the International Reference Life Cycle Data System (ILCD) handbook states that to quantify resource depletion at endpoint level all methods that have been evaluated until now are too immature to be recommended, the ReCiPe method could be used as an interim solution (European Commission's Joint Research Centre, 2011). The scarcity characterization factors of this method are based on the marginal increase in costs associated with the additional extraction of a resource (Goedkoop et al., 2009).

However, this dimension of scarcity will already be accounted for in the indicator on environmental impacts. Moreover, it can be argued that a proper scarcity indicator should go further and should reflect the driving forces behind scarcity for the specific (geographical) context in which the indicator will be used. As this study covers the recycling of WEEE in a European context, the strategic relevance of materials depends on their economic importance and supply risk.

Accordingly, for reasons of simplicity and the direct link to EU material policies, the scarcity indicator proposed in this paper is based only on the criticality concept developed by the Ad-hoc Working Group on defining critical raw materials (European Commission, 2010). The indicator combines the numeric values on economic importance (EI) and supply risk (SR) (Table 2). This implies that all materials present in WEEE, but not included in the non-exhaustive list of critical raw materials, are given an EI- and SR-value of zero. So no criticality is assigned to them and their fates will not affect the indicator value. This is the case for several WEEE-relevant materials, such as cadmium, bromine, bismuth, arsenic, tin and plastics. It is thus implicitly accepted that the current and future candidate critical raw materials selected by the Ad-hoc Working Group, reflect the concerns underlying European strategies to secure raw material access. This implies also that geological scarcity is not taken into consideration (e.g. gold is not included in the EU-list today).

Table 2
Overview of the indicator 'recovery of scarce materials'.

Indicator I_S	Recycled material criticality
Equation	$I_S = \frac{\sum_{i=1}^{m} W_i' * EI_i * SR_i}{\sum_{j=1}^{n} W_j * EI_j * SR_j}$
m: number of output fractions from the recycling process, destined for material recovery	
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 i present in the input of the recycling process	
EI: economic importance of the material (as identified by the Ad-hoc Working Group)	
SR: supply risk of the material (as identified by the Ad-hoc Working Group)	
Numerator	Total criticality of recycled target materials
Denominator	Total criticality of materials present in the input of the recycling process
Rationale	The indicator equals 1 in the hypothetical situation that all materials present in the input of the recycling process of which the supply is of concern to the EU, are completely recovered as target material(s) and desired impurities in output fractions.

3.3. Closure of material cycles (I_C)

In a perfect closed-loop recycling process, materials would be endlessly and completely recovered and reapplied in the very same application, avoiding the use of primary materials (European Commission's Joint Research Centre, 2010). This is the aspiration of, among others, the cradle-to-cradle concept (McDonough and Braungart, 2002). However, due to the second law of thermodynamics, recycling systems will never achieve perfectly closed material loops, since the entropy of the materials tends to increase during the recycling process (Friege, 2012). Furthermore, the outputs of recycling operations do not necessarily have a quality that allows a reuse in the original application. It is observed that such open-loop recycling often involves some form of 'cascading' or 'downcycling' in quality from high-value primary uses to lower grade products (Lewis, 2002).

Precious and special metals that are present in PWB represent a small share in the overall weight of WEEE. Nevertheless, they account for a relevant part of the (potential) value, making their recovery also interesting from an economic point of view. PWB can be separated by manual dismantling, after which the complete boards are fed into an integrated smelter. This way, a recovery grade of 90% and more can be achieved for Au, Pd and Ag. However, if PWB are shredded during the pre-processing of EoL-devices and then sorted automatically (e.g. by optical sorting), 25–75% of the precious metals can be lost (Chancerel et al., 2009).

Steel and aluminium parts can be recycled and reapplied as secondary material without causing dramatic changes in strength or chemical properties. In the case of steel, most producers are completely indifferent about the origin of the steel they purchase, as long as quality constraints are met. They may not even know whether they buy 'new' or 'recycled' material (Geyer and Jackson, 2004). Steel can make up an important part of the total material input weight, while most of the original quality and value are maintained. The aluminum alloy content from WEEE may be used again in the form of casting alloys for non-structural applications. Aluminum scrap is highly valued and its processing constitutes an economically relevant branch of the aluminum industry. An effective and efficient recovery of steel and aluminum is thus important to make recycling profitable.

Plastics make up an important part of the material value and weight of electronic equipment, making their recovery from WEEE economically desirable and, in some cases, necessary to meet the WEEE Directive recycling targets. Furthermore, WEEE plastics are observed to contain hazardous contaminants and other strongly regulated compounds, such as heavy metals and brominated flame retardants (Schlummer et al., 2007). The environmental impact and health hazard potential of chemicals like these can be seen as an extra factor increasing the relevance of closing plastic material cycles (Lithner et al., 2011). But plastic recycling is only an option if separation processes achieve a high-purity product (higher than 96%) (Dodbiba et al., 2008). Unfortunately, plastics are particularly difficult to recycle in a closed-loop scenario due to the huge variety of plastic resins and additives, which complicates sorting. Nonetheless, the observed development and integration of innovative sorting technologies over the last decade (Freegard et al., 2007; Williams, 2006; WRAP, 2009), have the potential to improve significantly the recycling of WEEE plastics. Another option consists in separating interesting plastics by pre-shredding treatments, such as selective dismantling (Vanegas et al., 2012a).

Recyclers attempt to recover the highest value from WEEE at the lowest costs. Recycled materials are sold on markets where they are valued according to their quality. One of the existing methods to account for quality losses due to recycling is the so-called Value Corrected Substitution (VCS) method (Wenzel et al., 1996). VCS uses market price devaluations as a measure of the material degeneration over a recycling system, in the event that no chemical or physical characteristics can be found to reflect the functionality of a material over the whole material cascade (Werner, 2005). A value-corrected credit reflects both the amount and quality of the secondary good, and can thus be used to quantify downcycling (European Commission's Joint Research Centre, 2010). This way, the recycled material value can be used as a proxy for the degree of cycle closure.

Considering the above, the use of the ratio of the market price of the output fraction that contains the target material(s) and the market price of the corresponding material used in the original application, is proposed here as an indicator to measure material cycle closure. However, in an ideal situation market value should be considered instead of market price, since secondary material markets might be inefficient and in disequilibrium, provoking differences between the market value and the price at which a secondary material is traded. Indeed, lower prices obtained for recycling process output fractions can indicate that (i) the corresponding materials can (or will) only be reapplied in lower valued applications, (ii) the particular secondary material market is limited, saturated or constrained (e.g. by regulations or procurement standards) or (iii) additional processing is required. Ekvall and Weidema (2004) therefore suggest that price elasticity of demand and supply for the recyclable material could be taken into account. This should offset eventual disparities between market value and actual price in an imperfect or incipient market. Nevertheless, in this study market price of recycled and original materials is used to limit the complexity of measuring the indicator. Because the indicator is meant to assess material cycle closure, only the market price of output fractions with effectively recovered target materials is considered. Neither treatment related costs for disposal or incineration of not recycled fractions, nor the costs of the recycling process itself, are used for this indicator (Table 3).

Table 3
Overview of the indicator 'closure of material cycles'.

Indicator I_C	Degree of material cycle closure
Equation	$I_C = \frac{\sum_{i=1}^{m} W_i' * V_i'}{\sum_{j=1}^{n} W_j * V_J}$
m: number of output fractions from the recycling process, destined for material recovery	
n: number of materials present in input of the recycling process	
W_i': weight of the output fraction that contains material i	
W_j: weight of material i present in the input of the recycling process	
V_i': current market price of output fraction i	
V_j: current market price of the material j, present in the EEE	
Numerator	Current market price of the recycled output fractions
Denominator	Current market price of the materials present in the EEE
Rationale	The indicator equals 1 in the ideal situation that all materials are recovered and the market price that can be obtained for the recycled materials, products or substances equals the current market price of the materials in the original device.

3.4. Avoided environmental burdens (I_E)

EU waste management policies primarily aim to reduce the environmental and health impacts of waste. However, quantitative assessments of environmental impacts of current industrial WEEE recycling processes are still limited (Bigum et al., 2012). Nevertheless, Life Cycle Assessment (LCA) methodologies have been providing a quantitative understanding of environmental impacts since decades (Boustead et al., 1996). Detailed procedures, permanently updated databases and comprehensive software enable a holistic and standardized approach.

Such LCA-based approach was employed by Huisman (2003) when introducing the QWERTY-concept. This concept focuses on the determination of 'Quotes for environmentally WEighted RecyclabiliTY' rather than weight-based recycling scores. The QWERTY approach allows calculating net environmental impacts associated with recycling, including the impact of hazardous substances when not recovered, the additional environmental burden of processing, transport, energy use and the avoided environmental impact by recycling instead of mining materials.

Such net environmental impact is composed of four elements: (C1) the burdens caused by the resource and energy requirements and the emissions of recycling processes, (C2) the credits for avoided emissions from virgin materials production due to the recycling of materials, (C3) the credits for avoided emissions from the substituted energy source due to recovered fractions that go to incineration with energy recovery, and (C4) the burdens caused by the disposal of residual material fractions that are not recycled (European Commission's Joint Research Centre, 2012).

The objective of the environmental indicator presented here is to assess the avoided environmental impact that can be achieved by recycling materials. Therefore, the benefits from energy recovery from incinerated fractions (C3) and the burdens of landfilling unused material fractions (C4) are not taken into consideration. In addition to this, also the burdens caused by the resource and energy requirements and the emissions of recycling processes (C1) were not taken into account as, in general terms, recycling preprocessing impacts are smaller than end-refining impacts, and both are greatly outweighed by the avoided environmental effects of primary material production.

Indeed, Hischier et al. (2005) showed that throughout the complete Swiss WEEE recycling chain the environmental impact related to size reduction, sorting and dismantling activities only constitutes a relatively low share of the total impact. The main impact occurs further downstream when purifying the sorted fractions (Hischier et al., 2005; Wäger et al., 2011). And in the case of **metals**, the overall environmental impact of WEEE recycling is dominated by the avoided mining and metallurgic processes of virgin ore, against which the impacts of the emissions and energy consumption of the recycling process itself can be considered relatively small (Bigum et al., 2012; Scharnhorst et al., 2006). This is particularly the case for precious and specials metals. For example, the ratios for gold, copper and aluminium between the inflicted environmental impacts of secondary production (including pretreatment and metallurgical refining) and the avoided environmental impacts of primary production are 0.004, 0.060 and 0.132 respectively,[2] showing that the recycling process impacts are of minor significance, even when energy intensive refining processes

[2] Calculated as ratios of single score impacts, using ReCiPe Endpoint (H/A Europe) V1.07. with inventory data from EcoInvent 2.0.

Table 4
Overview of the indicator ‘avoided environmental burdens’.

Indicator I_E	Avoided environmental burdens
Equation	$I_E = \frac{\sum_{i=1}^{m} W'_i * B'_i}{\sum_{j=1}^{n} W_j * B_J}$
m: number of output fractions from the recycling process, destined for material recovery n: number of materials present in the input of the recycling process W'_i: weight of target material(s) in the output fraction i W_j: weight of material i present in the input of the recycling process B'_i : environmental burden associated with the production of the material that is avoided by the recycled output fraction B_j: environmental burden associated with the production of the material present in the EEE	
Numerator	Environmental burden that is avoided by the recycling of the materials
Denominator	Total environmental burden generated by the production of the materials in the EEE
Rationale	The indicator equals 1 in the ideal situation of closed-loop recycling of all input materials. Its value decreases with reduced material weight recovery or when the output fraction substitutes a resource with a lower production burden than that of the production of the materials that compose the fraction. If desired, specific environmental impact categories can be accounted for (e.g. climate change or eco-toxicity).

are involved. Furthermore, Wäger (2011) demonstrates that the aggregated environmental impact per ton related to the production of ruthenium, gold, palladium and platinum outweigh the effects of, for example, aluminium production by a factor 10.000. This can be explained by the fact that precious and special metal are typically extracted from low-concentrated ores requiring energy-intensive mining and extraction steps and complex refining and production processes. Major future improvements of the environmental performance of WEEE recycling activities can thus be achieved by higher recycling rates of precious and special metals, that are currently lost especially in the pre-processing stage (Hagelüken and Meskers, 2010; Wäger et al., 2011).

For **plastics**, on the other hand, the main environmental benefit of recycling is achieved by avoiding the energy consumption of the production of the virgin polymer production (Boustead, 2005). The precise amount of energy saved will strongly depend on the polymer type that is being recycled, as well as on the degree of effective substitution of primary material and the amount of energy required by the recycling process (Tukker, 2002). It is observed that from the 1990s, recycling processes have been significantly optimized, especially in terms of electricity consumption (Garraín et al., 2007). If virgin plastics are effectively substituted, the energy consumption of the recycling process is often negligible in comparison with the large benefits from avoiding the use of primary materials, even in the case of recycling mixed waste plastics (WRAP, 2008).

Considering the above, the proposed indicator on the environmental performance of WEEE recycling processes is taken as the ratio of the aggregated environmental impact of the avoided mining and refining of target materials in the useful output fractions (C2) and the environmental impact of the production of the total material content in the input (Table 4). As a consequence of this simplification, only environmentally sound recycling processes and technologies should be assessed with the proposed indicator. Furthermore, it renders the indicator unsuitable to assess the effect of process energy and material consumption enhancements that do not affect the composition and quality of functional outputs.

3.5. Aggregation of indicators into a single recycling index

The different indicators presented in the previous paragraphs can be used as stand-alone indicators or can be combined into a Recycling Index (RI), for instance by applying a simple weighted sum model. This model uses weighting factors (a_i) for each of the composing indicators.

$$RI = a_1 I_W + a_2 I_S + a_3 I_C + a_4 I_E \text{with} \sum \mathrm{a_i} = 1$$

Public and private stakeholders might have different priorities and targets, hence resulting in differently valued weighting factors. Recycling facilities, for instance, will prioritize value recovery (cycle closure (I_C)), while waste management authorities will be more interested in achieving higher weight based recycling targets (weight recovery (I_W)). Ahlroth et al. (2011) suggest that one can achieve the broadest possible use of weighting systems when weights are based on monetary measures compatible with welfare economics. The ‘cycle closure’ indicator defined here already refers to market prices, and monetization of LCA results is common practice. However, a suitable method for monetizing the criticality dimension is yet to be proposed. In the meantime, it might be worthwhile to weigh the relevance of the criticality indicator in proportion to the weight share of materials in the input fractions for which criticality characterization factors were already determined.

Nevertheless, as shown by Jollands et al. (2003), the usefulness of such an aggregation for policy making and evaluation, has been subject to discussion. Composing a useful indicator requires a balancing act between, on the one hand, the amount of information that is lost in the simplification due to aggregation and, on the other hand, the information needed to support sound decision making in a context of European WEEE recycling in compliance with SMM.

In our opinion, further research is necessary, based on appropriate case studies in which the indicator set is used, to examine the utility of, and need for, such a simplification. Also the possible occurrence of co-linearity among the indicators requires further attention. Yet, the fact that, based on the discussions from the previous paragraphs, the proposed indicators seem to provide a cross-sectional representation of main factors of interest in a context of European WEEE recycling in a framework of SMM, is in favor of aggregation. Additionally, since all indicator values are relative to a theoretical, perfect recycling system, they can be assumed to be commensurable. Nonetheless, the challenge of setting appropriate weighting factors should be addressed first, preferably through participative methods that draw on expert knowledge from public and private stakeholders (Ghadimi et al., 2012).

4. Calculation example, results and discussion

The recycling indicators described in the previous sections were applied on a case study in which the EoL-treatment of a specific LCD television, i.e. the Philips 46” 9000 Series (2008), was assessed. This section reports about this case and aims to (i) demonstrate the way of calculating the indicators, (ii) to identify practical difficulties and limitations and (iii) to visualize different possible applications. Hence, the recycling process set-up (Fig. 1), recycling output qualities, employed yields and purities and fates of the recycled materials were chosen in function of these goals.

The input of the recycling process under consideration comprises the complete material composition of a specific LCD television model after removal of the power cord and the foot stand (Table 5). The process entails a manual dismantling step, in which the plastic back covers (BC) and part of the most valuable PWB, particularly the TICON and SSB[3] board, are removed. It is assumed that 75% of the PWB are taken out manually. The BC are re-granulated to produce

[3] TICON = Timing and Control; SSB = Small Signal Board.

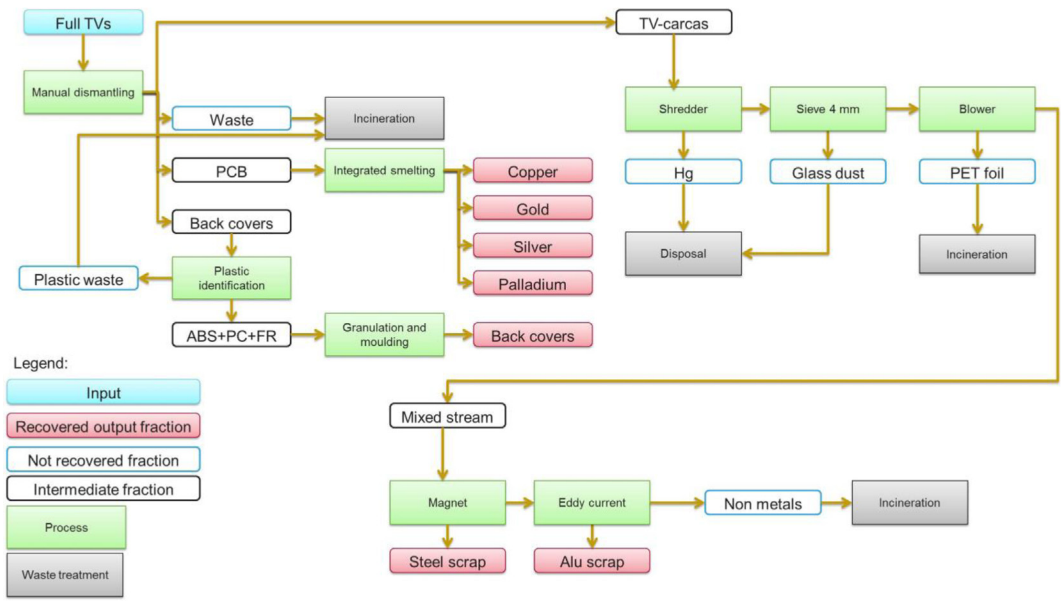

Fig. 1. LCD recycling process setup, system boundaries and output fractions. In fact 17 different metals are recovered by integrated smelting, only four were considered for the illustrative case study.

new BC in a closed-loop process (Vanegas et al., 2012b) and the removed PWB are sent to an integrated smelter for the recovery of a large number of metals, including gold, silver, palladium and copper. The remaining TV carcass is then fed into a shredder, equipped with a mercury removal system, after which the shredded fraction is sieved for dust removal. In a next step, a blower is added to remove foil fragments that might hinder further processing. Ultimately, the mixed output stream passes through a magnetic and an eddy current separation, from which a steel and an aluminum scrap fraction are obtained that are sent to the steel and aluminum industry respectively. The unrecovered fractions, containing mainly (LCD) glass fragments, plastics and the remaining PWB, are destined for waste treatment, which is not part of the recycling process under consideration in this study.

Manual dismantling, shredding and sorting steps will be referred to as ‘pre-processing’, the integrated smelting and re-granulation as ‘secondary processing’.

The composition of the output fractions containing target materials are shown in Table 6 and Table 7. These numbers are calculated from experimental process efficiencies, complemented with numbers from literature and expert estimates.

Table 5
Material composition of Philips 46″ 9000 Series (2008).

Material (metals)	g/TV	Material (other)[b]	g/TV
Al based metals	795	Plastics	
Fe based metals	13834	ABS + PC + FR in BC	3474
rPWB[a]	505	ABS + PC + FR rest	1038
Ag	0.4984	PET (white)	1054
Au	0.0869	ABS + PC	111
Pd	0.0086	PC	2328
Cu	128.77	PC + GF	472
Other PWB	1338	PMMA	1170
Ag	1.4571	PC	330
Au	0.2154	Glass	2760
Pd	0.0187	Hg (in CCFL)	0.077
Cu	276.97		
Total weight of TV in g:			29208

[a] Valuable printed wiring boards, particularly TICON + SSB boards.
[b] Acrylonitrite butadiene styrene (ABS), polycarbonate (PC), polyester (PET), polymethyl methacrylate (PMMA), flame retardant (FR), glass fiber (GF).

4.1. Indicator I_W

The indicator I_W on weight recovery equals 0.58. This number can be read as a recycling efficiency of 58% in terms of weight. Note that, as has been mentioned previously, under the current definition of the weight-based targets in the WEEE directive all materials entering the recycling facility are considered for the calculation of the recycling target. In the present case, the complete television offered to the first recycler would thus be considered as recycled. However, in line with the indicator here, all the materials that

Table 6
Target material weight of output fractions from pre-processing (per TV).

Output fraction	Fraction weight (g)	Fraction target	Fraction target weight (g)
ABS + PC + FR in BC	3300	ABS + PC + FR in BC	3300
Aluminum scrap	820	Al	664
Steel scrap	13549	Fe	13142
rPWB	379	Ag	0.3738
		Au	0.0651
		Pd	0.0064
		Cu	96.58

Table 7
Recycled target material after secondary processing (per TV).

Output fraction	Fraction target weight (g)	Secondary processing efficiency (%)	Secondary processing fraction purity (%)	Recycled target material (g)
ABS + PC + FR in BC	3300	90	100.00	2970
Aluminum scrap	664			664
Steel scrap	13142			13143
rPWB				
Ag	0.3738	97[a]	100.00	0.3626
Au	0.0651	98[a]	100.00	0.0638
Pd	0.0064	98[a]	100.00	0.0063
Cu	96.58	95[a]	100.00	91.75
Total recycled material				16869

[a] (Bigum et al., 2012).

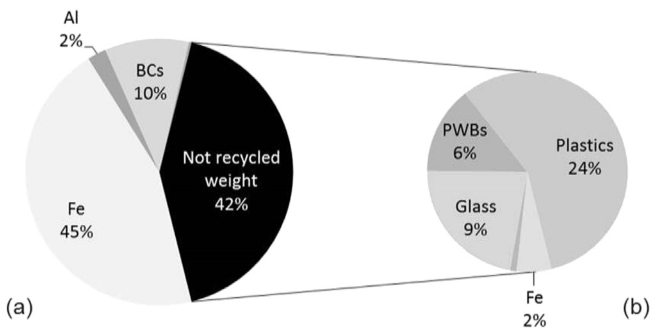

Fig. 2. (a) Shares of recycled target materials within the resulting value of indicator IW, (b) Opportunity for optimization of the recycling in terms of weight, expressed as individual shares of materials that are not recycled in the current analyzed EoL treatment.

ultimately end up in output fractions as undesired impurities, or go to incineration or landfill, are considered as lost.

Fig. 2a shows the weight shares of the materials that are recycled from the studied television at the end of the recycling process. As can be seen, three quarters of the recycling efficiency are due to the recovery of steel (Fe-based). PWB are only considered in terms of their precious metal and copper yield after refining; their relative weight contribution to the recycled fraction is less than one percent.

Fig. 2b unveils which material recycling efforts should lead to a better weight recovery. In this case study, most of the unrecycled weight corresponds to plastics. Also the not recovered glass and PWB have a relevant weight share.[4]

4.2. Indicator I_S

To calculate the indicator for supply scarcity, the numeric values for economic importance and supply risk, assigned to minerals and metals by the Ad-hoc Working Group, are used (European Commission, 2010). The resulting values, for the minerals and metals covered in the LCD-television case study, are given in Table 8.

As explained earlier, no strategic relevance due to criticality is given to plastic recycling. For the LCD glass, the criticality was estimated by considering the main critical materials contained in glass powder from waste LCD glass, as determined by Wang and Hou (Wang and Hou, 2011), that is SiO_2 (62.48%), Al_2O_3 (16.76%) and Fe_2O_3 (9.41%). As LCD glass also contains the critical element indium, a mean indium content per LCD television of 36.3 mg was considered (Forschungsinstitut Edelmetalle und Metallchemie and Institut für Energie- und Umwelttechnik, 2011). For PWB, the criticality of their respective content of critical materials was used, as shown in Table 9.

Indicator I_S is calculated to be 0.81, indicating that of the total amount of critical materials in the input 81% could be recovered. Fig. 3a shows that this high value can be explained by the recycled steel scrap. Due to their small weight share, precious metals, on the other hand, do not account for a significant amount of recovered critical materials. This may seem counter-intuitive, but from a strategic point of view, the economic importance of iron is high,

[4] In reality more materials are recycled from those PWB that are offered for secondary processing, such as hydrocarbons, tin, aluminum and silicon. However, for this illustrative case study, the effects of recycling these elements were not considered. They were assumed to be insignificant compared to the effects of not recycling the precious metals and copper contained in PWB that are lost before secondary processing.

Table 8
Criticality of minerals and metals.

Material	Economic importance	Supply risk	Criticality
Al	8.7	0.4	3.5
Cu	5.7	0.4	2.3
In	6.7	1.9	12.7
Fe	8.2	0.3	2.5
Pd (PGM[a])	6.7	3.6	24.1
SiO_2	5.9	0.4	2.4
Ag	5.0	0.3	1.5

[a] PGM include platinum, palladium, iridium, rhodium, ruthenium and osmium.

Table 9
Main critical material content of TV-components (printed circuit boards (PRIME, 2012) and LCD glass (Wang and Hou, 2011)).

Weight fraction (%) in component	rPWB	PWB (other)	LCD glass	Criticality
Ag	0.0987	0.1089	NC/NP	1.5
Au	0.0172	0.0161	NC/NP	–[a]
Pd	0.0017	0.0014	NC/NP	24.1
Cu	25.50	20.70	NC/NP	2.3
Al	12.60	12.43	5.87	3.5
Fe	NC/NP	NC/NP	6.59	2.5
In	NC/NP	NC/NP	0.0012	12.7
SiO_2	22.58	21.38	62.48	2.4

NC/NP: not considered or not present.
[a] As mentioned before, Au is not regarded as critical in the definition of the Ad-hoc Working Group.

while at the same time its large weight percentage contributes heavily to the indicator result.

Similarly, the unrecovered fraction (19%) shows on which materials or components to focus in order to maximize recovery. This is shown in Fig. 3b. As can be seen in this figure, the low relative weight of precious metals contained in the printed wiring boards, compared to the weight of the analyzed LCD television, makes the effect of an increased precious metal recycling from complete LCD televisions insignificant from the current EC criticality perspective. The recovery of LCD glass constituents and of copper from PWB, as well as an enhanced recycling efficiency for steel and aluminum scrap, are the only significant factors that could lead to a further improvement of the I_S indicator result.

4.3. Indicator I_C

As was discussed in paragraph 3.3, the indicator for material cycle closure uses the ratio of the market price of the recycled output, over the market price of the raw material (both of primary and secondary origin) used for manufacturing the original TV. The prices that were used in the calculation are presented in Table 10.

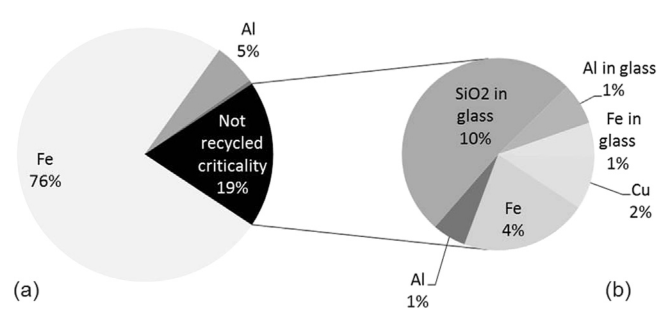

Fig. 3. (a) Shares of individual recycled materials within the resulting value of indicator I_S, (b) Opportunity for optimization of the recycling from the viewpoint of supply scarcity, expressed in shares of individual materials that are not recycled in the analyzed EoL treatment.

Table 10
Market prices (October 2012).

Material	Market price (€/ton)	Source (*)
Fe	521	1
Fe scrap	274	2
Al	1777	3
Al scrap	1160	3
Ag	786,000	4
Au	4,221,100	4
Pd	1,462,900	4
Cu	6749	3
ABS-PC (+FR) (virgin)	2685	5
ABS-PC (+FR) (recycled)	2000	6
PC + FR	4179	5
PC + GF	4023	5
PMMA	3000	6
PC	3100	5
PET	1917	5
LCD Glass	150	6
Hg	41,000	3

(*) Sources: 1 = www.worldsteelprices.com; 2 = www.meps.co.uk; 3 = www.metalprices.com; 4 = www.kitconet.com; 5 = www.plasticnews.com; 6 = (PRIME, 2012).

The resulting value of the indicator is 0.25, meaning that 14.30 euro is recovered from an input material price of 57.06 euro per television.

In Fig. 4a can be seen that the recycled plastic back covers, steel scrap and gold contribute most to the recovered value. In addition, Fig. 4b shows that, if cycle closure is a strategic priority, changes in the recycling process should focus on recovering plastics (mainly PC, PMMA and ABS-PC, with and without flame retardants. As a result of their gold content, also a more selective separation of PWB from other material fractions should be given priority (e.g. by more intensive manual dismantling or additional mechanical sorting equipment).

4.4. Indicator I_E

Environmental impacts are calculated by using the LCA-method of ReCiPe Endpoint (H/A Europe) V1.07. For the calculation of the environmental impacts related to the production of the materials in the analyzed TVs, inventory data from EcoInvent 2.0 were used. They represent average material production processes, taking into account that raw materials in waste products offered for recycling often originate partly from secondary sources. For example, the EcoInvent record '*Gold, at regional storage*' counts 68% primary gold production from mining and 32% secondary gold from recycling activities.

The environmental impacts due to the raw material production for making the TV, as well as the impacts that are avoided by the recycled materials, are expressed as a single score in mPt/kg, using Europe ReCiPe H/A weighting factors, as presented in Table 11. As mentioned in paragraph 3.4, also specific environmental impact categories could be selected to calculate the indicator. In that case, the exclusion of other categories must be taken into account when interpreting the resulting indicator value.

Table 11
EcoInvent records used for each material fraction and calculated single score impacts.

Material fraction	EcoInvent 2.0 record	Single score impact (mPt/kg)
Materials[a]		
Fe based	Steel, converter, low-alloyed, at plant/ RER S	442
Al based	Aluminium, production mix, at plant/ RER S	778
Ag (in PCB)	Silver, at regional storage/RER S	47400
Au (in PCB)	Gold, at regional storage/RER S	9,510000
Pd (in PCB)	Palladium, at regional storage/RER S	7,680000
Cu (in PCB)	Copper, at regional storage/RER S	3450
ABS + PC (+FR)	ABS, at plant/RER S (15%), PC, at plant/ RER S (75%), additives and/or FR (10%)[b]	620
PC + FR	PC, at plant/RER S	654
PC + GF	PC, at plant/RER S	654
PMMA	PMMA, beads, at plant/RER S	660
PC	PC, at plant/RER S	654
PET	PET, granulate, amorphous, at plant/RER S	320
Glass	LCD glass, at plant/GLO S	503
In (in glass)	*Indium, at regional storage/RER S*	23100
Hg	Mercury, liquid, at plant/GLO S	1,160000

[a] All recycled materials are assumed to replace the same materials as in the input.
[b] No impact data are available for additives, neither for FR.

For each output fraction from the recycling process, the substituted resource was selected that matches best with the characteristics of the material fraction at the system boundaries presented in Fig. 1. The fractions containing recovered steel and aluminum are assumed to be directly sold to the steel and aluminum industry thus substituting virgin steel and aluminum. Although the ILCD Handbook (European Commission's Joint Research Centre, 2010) recommends to give credits as for virgin production impacts in a growing market for secondary materials, it was chosen to use the impacts associated with the market mix in this case as the use of virgin production impacts might result in environmental benefits being larger than the original material burdens calculated starting from the market mix including secondary material.

For the manually removed PWB a further refining step was included within the system boundaries, leading to the production of metallic gold, silver, palladium and copper, which were assumed to

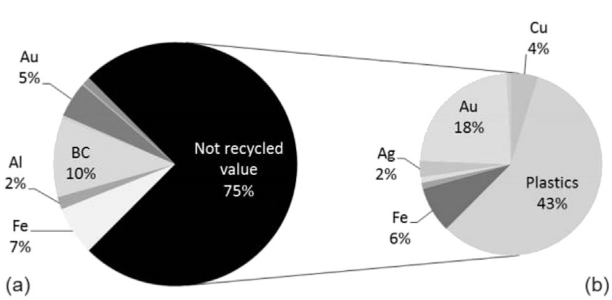

Fig. 4. (a) Shares of individual recycled materials within the resulting value of indicator I_C, (b) Room for optimization of value recovery and material cycle closure, expressed in shares of individual materials that are not recycled in the current system.

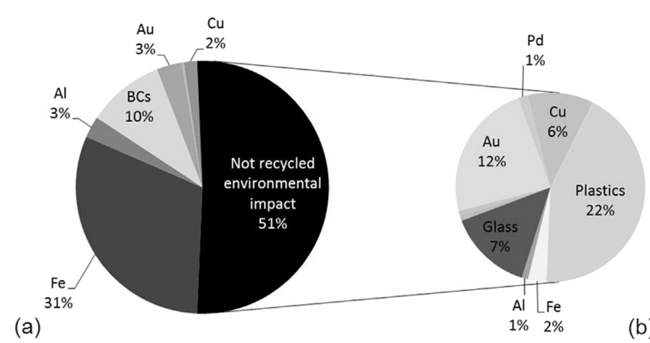

Fig. 5. (a) Shares of individual recycled materials within the resulting avoided environmental burden of indicator I_E, (b) Opportunity for optimization of the avoided environmental burdens by recycling, expressed in shares of individual materials that are not recycled in the analyzed EoL treatment.

be substituting for the respective metals available on the international market. The dismantled BC are assumed to be re-granulated for re-use in new BC. Following the principle of closed-loop recycling, virgin plastic can in this case be seen as avoided material.

The resulting indicator value is 0.49, meaning that about 49% of the environmental burdens from the original material content of the TV are avoided by recycling the device. These environmental benefits are dominated by the closed-loop recycling of steel, BC plastics, aluminum and the recovery of gold from the dismantled PCB, as can be seen in Fig. 5a.

Fig. 5b presents the environmental benefits that could be achieved by optimizing the recycling process towards the recovery of the currently not recycled material content, i.e. the materials that are lost as impurities, incinerated or disposed of. The diagram illustrates that gold, copper, plastics (mainly PC) and glass dominate the environmental profile of this particular LCD TV, despite their low contribution to the total weight. Again, this reveals the relevance of achieving higher rates of recovery of metals contained in PWB, particularly gold and copper, to substitute partly for primary metal mining, which has a huge environmental impact. Yet, since metal losses in a secondary smelting process are generally very small, minimizing the loss of PWB during the sorting and separation process of LCD televisions would improve the environmental performance of the recycling process. It is observed that improved recycling of plastics is also relevant from an environmental point of view.

4.5. Case study conclusions

The indicators calculated in the previous paragraphs can be presented graphically as in Fig. 6. This figure shows that the recycling system for the Philips 46" 9000 Series LCD television presented in this paper scores high on 'recovery of critical materials', moderate on 'weight recovery of target material(s)' and 'avoided environmental burdens', and rather low on 'closure of material cycles'. When single score environmental impacts are used for the environmental indicator, as has been done in the case study here, the last two indicators may tend to co-linearity, especially with a higher degree of internalization of environmental costs into materials' market prices and with a higher share of materials' market prices determined by the resource intensity of their production. When, on the other hand, the environmental indicator is restricted to one or more midpoint impact categories, co-linearity between these two indicators might be inexistent.

As can be concluded from the previous paragraphs, optimization of the LCD television's recycling system can be achieved by extending the system with the recycling of the different polymers into high-quality plastics. In this way, weight and value recovery (cycle closure) can be optimized and more environmental impacts can be avoided. However, this will not affect the value of the criticality indicator, as plastics are not included in the EU-list of raw materials for which criticality was analyzed. Another possibility is to focus on the recovery of the LCD glass constituents or components, such as the glass substrate and indium. This would significantly improve the value of most indicators, with a lesser effect on the one for cycle closure. This is because the value of LCD glass resides mainly in the complex technologies applied to obtain the LCD functionality, rather than in the raw materials contained in it.

Indeed, in the case study pie charts it is observed that for each indicator different materials dominate the 'not recycled' fraction. Therefore, a change in the recycling system will have a different effect on each indicator, hindering a comparison between optimization options. This problem could be dealt with by developing a weighting method, as has been proposed under Section 3.5, which would enable the comparison between recycling systems that generate different output fractions. This way, the performance of a recycling process set-up with manual removal of PWB before shredding could be compared with one without previous removal. Weighting would also facilitate producers of electronic equipment to assess the recycling performance of alternative designs with different material compositions that are fed into a defined recycling system, for example the studied Philips model and a similar model with a higher aluminium content at the expense of the use of steel alloys. If, purely hypothetical, the manufacturer replaces 80% of the steel contained in the case study television by an identical volume of aluminium (assuming densities of 2800 and 7850 kg/m^3 for aluminium and steel respectively), the same recycling process recovers 24% less of the total (diminished) television weight (see Fig. 7). Indicator values on environmental impacts and criticality decrease by 13%. Cycle closure, however, increases with 11%, which means that more value is recovered from the (only slightly more valuable) aluminium based television.

This example illustrates how the indicator set can be used to identify opportunities for the optimization of WEEE End-of-Life scenarios and to assess the effects of recycling optimization strategies. Such strategies might consider changes in material composition and/or architecture of the products fed into a particular process (e.g. replacing steel by aluminium), as well as alternative process set ups to recycle a specific input (e.g. different (pre-) treatment options for cell phone recycling). When simulating or

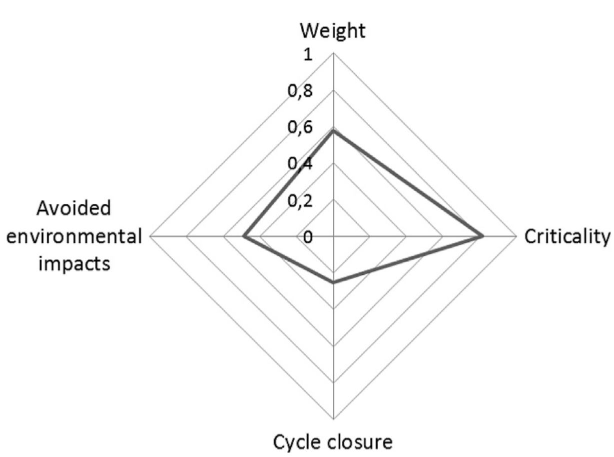

Fig. 6. Case study recycling performance.

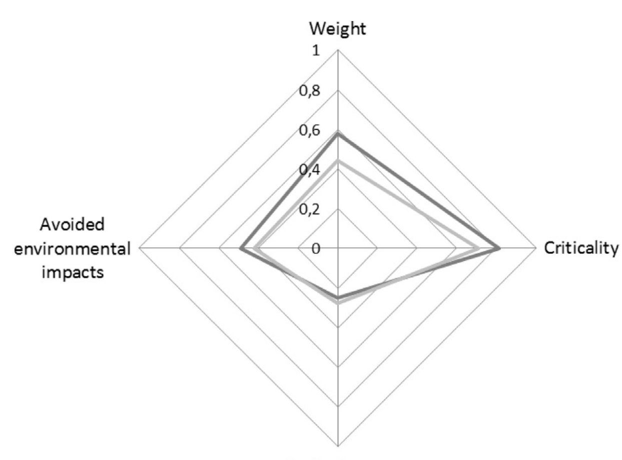

Fig. 7. Recycling performance Fe-based (dark line) versus Al-based television (light line).

estimating the output characteristics of the recycling of an alternative model, it is important to be aware that also the way the device is constructed (e.g. whether parts are screwed or glued to each other) will influence the output characteristics and thus the indicator results, apart from the input material composition.

Another interesting observation from the case study is that calculating the indicators is only feasible when data can be obtained on the quantities and qualities of materials that leave the recycling system. The development of simulation software contributes greatly to such data availability. It is also noted that the recast of the WEEE Directive requires Member States to ensure output records are kept, "*with a view to analyzing the feasibility of setting targets on the basis of products and materials resulting (output) from the recycling processes*" (European Parliament, 2012). Furthermore, the outputs at the system boundaries of an analyzed recycling process must be products, materials or substances that can be used for the original or other, possibly lower, quality purposes. If this is not the case, the share of avoided environmental impacts to be allocated to the studied system will have to be determined. Where further refining or upgrading of an already usable output fraction is an option, its effects can be analyzed, e.g. to optimize trade-offs between the strategic sustainability gains that are shown by the indicator set and additional treatment requirements.

A final observation, and remark, is that the indicators refer to the performance of recycling systems that aim to recover the functionality of the input materials. They do not cover complete product life cycles that include production, (re-)use, collection, remanufacturing, etc. of the (mix of) devices that ultimately are fed into the recycling process that is being assessed. If the process input consists of one single type of appliance, as was the situation in the case study presented here, the denominators of the indicators give an idea on sustainability attributes of that particular type of device. Indeed, from a product life cycle perspective, the sustainability gains of using a higher share of cheap, abundant and low resource intensive materials to build a device might well outperform the benefits of optimizing a recycling system for that same device, even if these low impact materials were not recycled at all. Analogously, an excellent recycling process performance can be expected from devices that contain high concentrations of precious metals that are successfully routed into the copper fraction. While in order to decrease the product life cycle environmental impacts, the lowering of precious metal use in the product would be far more recommendable.

5. Conclusions

This paper presents and discusses the development of a comprehensive set of indicators to practically and quantitatively assess the effectiveness with which a recycling system aligns with strategic sustainability goals concerning WEEE recycling in a European context, beyond the quantification of the weight of recycling process input materials. The indicator set is based on the first of the OECD sustainable materials management principles, i.e. 'preserve natural capital', and translates from a product centered approach the preservation ideas underlying this principle into four touchstones for assessing and monitoring impacts related to recycling systems, namely 'weight recovery of target material(s)', 'recovery of critical materials', 'closure of material cycles' and 'avoided environmental burdens'. These four indicators can be calculated when the material compositions of the input and output of a WEEE recycling process are known as well as the purity, market price and functionality of the output fractions. Regarding criticality, it is proposed to make use of the values obtained from the relative, quantitative assessment on criticality of raw materials, carried out under the chairmanship of the European Commission services, introducing a new aspect in the indicator debate.

The operability of the indicator set has been illustrated by a case study on the recycling of the Philips 46'' 9000 Series LCD television, which showed the usefulness of the indicator set to identify opportunities for improving sustainability effects of recycling systems. More specifically, the case showed how different choices concerning product design and/or recycling process set-up will result in different indicator values. A comparison of these values allows visualizing the trade-offs that have to be addressed in order to optimize the recycling performance. In addition to this, the case study also made clear that meaningful outcomes can be obtained, while the quality of the indicator results increases with the level of detail, preciseness and accurateness of the available data. As has been discussed in this paper, even with the introduction of some simplifications, for example the use of average process efficiencies or ex-ante estimates of outputs, a first impression can already be gained on the effect of modifications in product material composition or recycling system setup on a WEEE recycling process' performance.

Our future research will focus on a further optimization of the indicator set to compare ex-ante and ex-post the sustainability of alternative recycling systems and product designs. Further research should also elucidate whether the indicators sufficiently comply with the CREAM criteria of being clear, relevant, economic, adequate and monitorable (Kusek and Rist, 2004). The uncertainty, incompleteness and simplifications involved in the numerics that are used can be decreased by (i) integrating the environmental burdens related to the recycling processes themselves, (ii) extending and updating the list of materials considered for criticality analysis, (iii) incorporating other attributes of scarcity, as proposed by Graedel et al. (2012), (iv) enhancing the reliability and accuracy of background data on environmental impacts of primary and secondary material production, and (v) extending the indicator set with additional sustainability aspects such as social impacts of WEEE recycling processes and toxicity control. The latter will involve a trade-off between the resource potential of toxic elements, already taken into consideration by the current indicator set, and the need to provide safe sinks to avoid dispersion of toxic elements. However, such broadening of scope and accuracy should be balanced with the intended simplicity and ease of calculating the indicators. Finally, also the usefulness of integrating the four indicators into one single recycling index will be dealt with in future research, as well as the weighting issue that is inextricable linked to this. The development of a method for monetizing the criticality indicator results might open perspectives to a broader use of a weighted index quantifying recycling process benefits.

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