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Identification and assessment of product's measures to improve resource efficiency: the case-study of an Energy using Product

Fulvio Ardente*, Fabrice Mathieux

European Commission – Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749, 21027, Ispra, Italy

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ABSTRACT

The article introduces the "Resource Efficiency Assessment of Products" (REAPro) method to assess and improve the resource efficiency of Energy Using Products, with a special focus to their end-of-life. The method allows to identify product's hot spots relevant for the following criteria: reusability/recyclability/recoverability (in mass and in terms of environmental impacts); recycled content (in mass and in terms of environmental impacts); use of hazardous substances. The method is structured into five steps: characterization of the product; assessment against the selected criteria; identification of product's hot spots; identification of improvement measures (at the product level); assessment of policy measures for resource efficiency (at the 'product group' level). The method includes the calculation of a comprehensive set of lifecycle based indices, including some original indices, as the "Reusability/Recyclability/Recoverability benefits rates" and the "Recycled content benefit rate". The method is applied to a case-study Liquid Cristal Display (LCD) television. Some exemplary measures to improve resource efficiency of television are discussed as: the improvement of products recyclability through the setting of thresholds of the time for dismantling; the setting of a minimum recycled content of large plastic parts; the declaration of the content of indium in the displays. Potential environmental benefits associated to these measures have been estimated. The method also proved to be relevant to current European Union (EU) policies and some of the presented results are being used as input for some on-going policy processes.

1. Introduction

Products have important environmental impacts during their life cycle, but "once a product is put on the market, there is relatively little than can be done to improve its environmental characteristics" (EC, 2001). It is therefore necessary to integrate environmental considerations throughout the whole production process, and in particular, during the early phases of product development (ISO, 2002a; Luttropp and Lagerstedt, 2006). "Complex product manufacturers should improve the design of their products more and more in relation to their end-of-life treatment [...]. Recovery activity [...] varies strongly among regions and countries and is quickly evolving. Not only currently available recovery technologies but also promising ones for the future should therefore be considered by manufacturers when designing products" (Mathieux et al., 2008).

The EU Waste Framework Directive (2008/98/EC) underlined the need to identify prevention measures, including "the formulation of a product eco-design policy addressing both the generation of waste and the presence of hazardous substances in waste, with a view to promoting technologies focussing on durable, re-usable and recyclable products" (EU, 2008). In, 2011 the European Commission (EC) published the "Roadmap to a Resource Efficient Europe" identifying the use of waste as one of the European Union (EU) key resources to lower the dependence on imports of raw materials and to lower impacts on the environment (EC, 2011a). Similar concepts related have been also highlighted by the UNEP Resource Panel (UNEP, 2011).

The European roadmap on resource efficiency also set some strategies and milestones for the next future, as the improvement of the quality and quantity of recycling and the progressive limitation of energy recovery and landfilling (EC, 2011a). The EC aims, among the others, to stimulate the secondary materials market and demand for recycled materials through developing end-of-waste criteria as (EC, 2011a): minimum recycled material rates, durability and reusability criteria and extensions of producer responsibility for key products. Furthermore, the improvement of

* Corresponding author. Tel.: +39 0332 785698; fax: +39 0332 786645.
E-mail address: fulvio.ardente@jrc.ec.europa.eu (F. Ardente).

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recycling rates of materials can be very effective to reduce supply risks, especially for material that are critical for the economies (EC, 2010c).

1.1. Criteria for resource efficiency of products

The principles of the EC roadmap and of the waste directive have been already put into practice in several pieces of legislations as, for example, in the setting of minimum recycling and recovery rates (in mass) for Waste of Electrical and Electronic Equipment (WEEE) (EU, 2012) or in the setting of minimum thresholds for some product's criteria as reusability/recyclability/recoverability – RRR – (in mass) for new vehicles (EU, 2005). The objective is the improvement of the product's resource efficiency throughout its whole lifecycle. Principles of the ecodesign have been also applied by the EU to the recent Directive "for the setting of ecodesign requirements for energy-related products (ErP)" (EU, 2009).

Measures for the improvement of the product's resource efficiency can be identified taking into account some of the basic strategies of eco-design (reduction, reuse and recycle, recovery and treatment for disposal) (Cellura et al., 2012). Conscious that the improvement of the product's performances often involves several possible strategies, it is envisaged to develop tools to support designers and policy makers in the assessment of possible ecodesign measures (Ardente et al., 2003; Mathieux et al., 2008; Gehin et al., 2008; Lelah et al., 2011). These should be also evaluated in terms of potential benefits and costs achievable at the product group level, including the assessment of best available technologies in comparison with average products available on the market (VHK, 2011).

The MEErP (Methodology for the Ecodesign of Energy-related Products) (VHK, 2011) has been developed by the EC for the identification of relevant energy-related measures in the European Ecodesign policy context. However, several stakeholders (including associations of consumers, non-governmental organisations and representatives of Member States) recently highlighted the need of more systematic and comprehensive assessments of other resource efficiency aspects, including those related to the end-of-life (EoL) of products (DEFRA, 2011; VHK, 2011; BIOis, 2013). In particular, it is recognised that lack of robust methods is one of the barrier for the integration of resource efficiency issues into product policies (Dalhammar and Machacek, 2013).

The development of methods, standards and tools for the measurement/assessment of resource efficiency criteria is therefore necessary and also encouraged by the legislation as in article 7.4 of the Directive on the EoL of vehicles, which states that the EC "shall promote the preparation of European standards relating to the dismantlability, recoverability and recyclability of vehicles" (EU, 2000). A first method for the calculation of the recyclability/recoverability rates has been illustrated by the standard ISO 22628 (2002b) based on the analysis of the Bill of Materials (BoM) and of the architecture of new vehicles, and on the consideration of proven technologies for the treatments of waste (ISO, 2002b). Recently a similar standard has been developed for the calculation of the RRR rates for Electrical and Electronic Equipment (EEE) (IEC, 2012).

Although these methods represent an important development for the assessment of RRR, some authors criticized the exclusive use of mass-based indicators because insufficient. This concept has been repealed also by the IEC/Technical Report (TR) 62635 (IEC, 2012), which recognized that "the calculation of recyclability rate based on the product mass approach is not the only the criteria to ensure a material efficient design (e.g. for rare materials)". On this issue, Huisman et al. (2003) highlighted that recyclability on weight basis is likely to lead to incorrect decisions. The calculation of the recyclability "should indicate and prioritize from an environmental perspective the avenues for product (re)design for end-of-life treatment" (Huisman et al., 2003). In fact, a material could be not relevant in terms of mass, being relevant in terms of contribution to the lifecycle impacts of the product (Mathieux et al., 2008; Ardente and Mathieux, 2012). Recyclability in environmental terms aims also at increasing the 'recycling quality' meaning the "maximum retention of value from recyclates for producing high quality recycled products with relatively low impact on the environment" (Ravi, 2012).

Another key issue is the promotion of recycled content for the production of certain materials. On this topic the ILCD Handbook (EC, 2010a) concluded that if the amount of a certain material "that is available via reuse/recycling/recovery is higher than the demand, and the market value is accordingly below zero, the main necessity is to increase the demand for the secondary good (i.e. recycled content) and/or its technical quality [...], but not the simple recycling rate". Some materials, as for example metals, are largely recycled due to the high value of the recycled material compared to the virgin one (Villalba et al., 2002).

Potential target materials for recycled content measures could be, for example, plastics (Froelich et al., 2007; Hopewell et al., 2009). The increase of recycled content of plastics also produces relevant environmental benefits (Froelich et al., 2007; Ardente et al., 2009). Some examples of measures for the promotion of recycled content of plastics into EEE have been already introduced in the current EU policies, as in the EU Ecolabel (EC, 2011b).

The reduction of use of hazardous substances is also a potential strategy to improve the resource efficiency of products by reducing the production of hazardous waste and improving the RRR of products. Possible related Ecodesign strategies are: the minimization of the use of hazardous substances in product (Donnelly et al., 2006), the identification of alternatives to hazardous substances (Knight and Jenkins, 2008), the reduction of the amount of hazardous waste during production (Wood et al., 2010) or the improvement of EoL treatments of hazardous waste (Ravi, 2012). These strategies have been also applied by some legislation to restrict use of hazardous substances (EU, 2006; EU, 2011) and improve the management of hazardous waste (EU, 2012).

Durability is certainly a key ecodesign aspect since lifecycle impacts of products relate to the lifetime (Ardente et al., 2005). This is particularly relevant for Energy using Products (EuP) or Energy Related Products (ErP), being that an increased lifetime would affect the energy performances of the product, potentially delaying the substitution with more energy efficient solutions, as for example, for energy plants (Ardente et al., 2005) or for buildings and building materials (Ardente et al., 2006, 2011). Methods for the measurement and assessment of product's durability are still an open issue, under debate in the scientific literature (Ardente and Mathieux, 2013). Possible strategies to improve product's durability include: minimum lifetime (measured according to standardized method as (CIE, 2005)), reparability and maintainability (Kostecki, 1998; Brook Lyndhurst, 2011), remanufacturing (Östlin et al., 2009), upgradability (Sundin and Bras, 2005; Brook Lyndhurst, 2011), improved warranties/guarantees (Brook Lyndhurst, 2011). Finally, further ecodesign criteria that have been identified as potentially relevant for the assessment of resource efficiency of products are: design for resource reduction (i.e. dematerialisation (Gottberg et al., 2006)) and design for use of renewable materials (EC, 2001). However, methods to quantitatively assess these criteria are still to be developed.

1.2. Aim of the article

The development of method for resource efficiency consists of investigating available ecodesign tools and criteria, analysing their compatibility, adapting/improving the most promising ones and testing them through use on sample products (Knight and Jenkins, 2008).

The Life Cycle Assessment (LCA) methodology (as standardized by the (ISO, 2006b)) is largely recognized by the scientific community as an effective tool to select environmental fields of attention and to validate ecodesign options for products (Brezet et al., 1999; Hunkeler and Vanakari, 2000; Muñoz et al., 2006). However, LCA provides several environmental impacts figures, which cannot be directly implemented into product design (Gehin et al., 2008). The key issue is therefore to develop methods to handle complex information related to different life cycle aspects, and to derive from this possible improvement measures.

The present article illustrates the REAPro method (Resource Efficiency Assessment of Products). The scope of the method is the assessment of resource efficiency of EuP/ErP. The main characteristics of the method are:

- It is based on a life cycle approach, which provides a comprehensive picture of the product's performance and identifies improvement potentials. Compared to majority of other Eco-design tools in the literature (Fleischer and Schmidt, 1997; Saling et al., 2002; Maxwell and van der Vorst, 2003; Ardente et al., 2003; Kobayashi et al., 2005; Le Pochat et al., 2007) the REAPro is specifically focused to the identification and assessment of potentially relevant ecodesign measures for various product policies.
- it integrates a set of robust and relevant product's criteria, as identified in the scientific literature:
  - ○ Reusability/Recyclability/Recoverability (RRR) (in mass and in terms of environmental impacts);
  - ○ Recycled content (in mass and in terms of environmental impacts);
  - ○ Use of hazardous substances (HS).
- It integrates a set of various indices related to the selected criteria. Indices have been originally modified/developed for the scope of the analysis (see Section 3 for details).

Some of the proposed indices are based on a life cycle approach. However, the method is not intended to provide a comprehensive

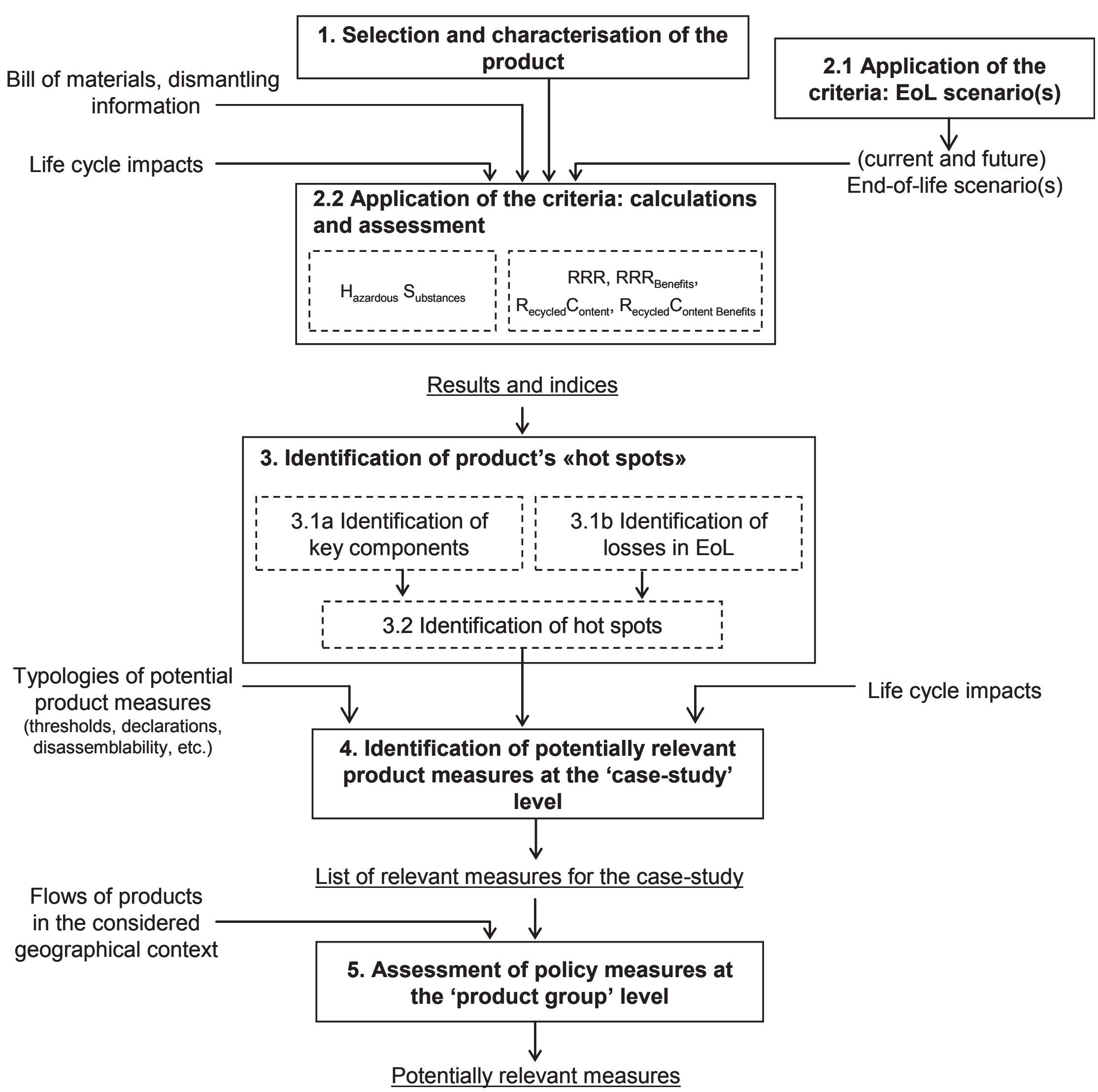

Fig. 1. Method for the identification and assessment of product's resource efficiency measures.

and detailed LCA of the product, but it aims at identifying product's measures that brings relevant life cycle benefits.

The article is subdivided into three parts: the first part focuses on the presentation of the REAPro method; the second part introduces the proposed indices; the last part applies the method to a case-study product (a Liquid Cristal Display (LCD) Television) identifying and discussing some product's measures potentially suitable for different policies.

2. Method for the identification and assessment of product's measures

The present section introduces the REAPro method for the identification and assessment of ecodesign measures to improve the resource efficiency of products. The method is composed by the following steps (Fig. 1):

Step 1. Selection and characterization of the product. This step includes the selection of the product group and the analysis of some representative case-study products. Data about the product(s) (BoM, disassembly information, lifecycle impacts) are collected/calculated.

Step 2. Assessment of the product against the selected criteria. This is further subdivided in:

2.1 Definition of EoL scenario(s). EoL scenario(s) for the selected product group are defined, representative of the current (or future) EoL treatments in the considered geographical area.

2.2 Calculations and assessment. This step includes the calculation of qualitative and quantitative indices for the selected criteria.

Step 3. Identification of product's resources efficiency EoL hot spots. Hot spots are those product's parts that are relevant for

Table 1
Type of product's measures to improve EoL resource efficiency of products (adapted from EcoDEEE (2008) and Ardente et Mathieux, (2012a)).

Type of product's measures			Criteria related to the measure		
Type	Sub-type	Examples (reference)	RRR	Recycled content	Use of haz. substances
Declaration of indices	General indices	"Manufacturer shall declare the recyclability rate of the product (IEC/TR 62635, 2012)";	X		
		"Manufacturer shall declare the recycled content of the product (EN 15343, 2007; SCS, 2011)"		X	
	Indices restricted to some specific material	"Manufacturer shall declare the recyclability rate of plastic parts (Ardente et Mathieux, 2012a)"	X		
		"Manufacturer shall declare the recycled content of packaging (IEEE, 2009)"		X	
Threshold of indices	General indices	"Recyclability benefit rate of the product for the Abiotic Depletion indicator shall be minimum X%" (Ardente et Mathieux, 2012a)	X	X	
	Indices restricted to some specific material	"Minimum threshold of the recyclability of plastic parts in the product" (Ardente et Mathieux, 2012a)	X	X	
Design for recycling	Use of compatible materials	"For materials that are not separable, prefer types of polymers or of metals that are compatible" (Renault, 1994; Castro et al., 2005; Froelich et al., 2007)	X		
		"Minimise number of different types of materials (including additives for polymers and alloys for metals)" (Dowie, 1995; Graedel and Allenby, 1996; Johansson, 1997; Froelich et al., 2007)			
	Use of materials more recyclable	"Large polymer parts that are addressed to manual dismantling shall be constituted preferably by: ABS, HIPS, PP, P/E, PP + EPDM, PP-GF, PC, ABS-PC, PA, PA-6, HDPE, SAN" (Mathieux, 2002; Mathieux et al., 2008)	X		
	Use of recycled materials	"Plastic case of the system unit shall have a post-consumer recycled content of not less than 10% by mass" (EC, 2011b)		X	
	Reduce number of contaminants	"Avoid coating (metal, plastic film, painting, textile, film, etc.) on plastics parts" (Graedel and Allenby, 1996)	X		
Design for disassemblability/ dismantlability	Time based index for dismantling	"Thresholds for the maximum time for the disassembly" (IEEE, 2012)	X		X
	Time based index based on mass/components	"Thresholds for the maximum time for the disassembly of Printed Circuit Board" (Ardente et Mathieux, 2012a)	X	X	X
	Reduction/simplification of fastenings	"Minimise number of fasteners and/or prefer fasteners easy to be removed" (Dowie, 1995; Graedel and Allenby, 1996; Johansson, 1997)	X		X
Dematerialization	Design of components for optimal use of materials	Minimise weight of the product for the accomplished function (EcoDEEE, 2008)	X		
Declaration of substances	Declaration of relevant substances	"marking of plastic parts containing flame retardants" (ISO 1043-4)			X
		"Content of indium in the product" (Ardente et Mathieux, 2012a)	X		
Threshold of substances	Thresholds (including banish) for the use of some relevant substances	"Content of mercury in the product should not exceed X milligrams" (EC, 2010b)	X		X
Marking/labelling/tracing	Easy identification of recyclable materials/parts	Use of different marking techniques (labels, marking, colour, tracers, magnetic dust, etc.) (EcoDEEE, 2008; Bezati et al., 2011)	X	X	X
	Identification of pollutants	Labelling of parts containing relevant substances (Ardente et Mathieux, 2012a)	X	X	X
	Use of innovative technologies for the automatic sorting systems	Use of tracing substances in polymers (e.g. magnetic powders, rare earths, etc.) for the marking of recyclable parts (Bezati et al., 2011)	X		X
Provision of information	Relevant information to be provided	"Information form manufacturer about EoL treatments of the products" (EU, 2012)	X	X	X

Table 2
Information about the case-study LCD-TV and about associated EoL scenarios.

Component	Mass [g]	Component details	EoL scenarios	
			1. Manual dismantling scenario	2. Mechanical treatment (shredding) scenario
Front cover/back cover/support	1510	HI-PS (50% of the plastics contain flame retardants)	Manually dismantled for recycling/recovery	The product is shredded with some manual + mechanic treatments for sorting, as: - Mercury from lamps is separated by specific plants to avoid contaminations; - PCB partially sorted by post-shredding hand-picking. - Metals partially separated (magnetic + eddy current sorting). - Shredded plastics partially sorted (by density systems). - Other parts are energy recovered or landfilled
Metal frames (various)	1923	Iron/steel	Manually dismantled for recycling	
	383	Aluminium		
Plastic frames	15	PC	Manually dismantled for recycling/recovery	
	136	Plastics (various)		
Printed Circuit Board (very rich)	59	Various (including hazardous substances and precious metals)	Manually dismantled and sorted (on the basis of content of precious metals)	
Printed Circuit Board (rich)	307			
Printed Circuit Board (poor)	308			
LCD	473	Glass, plastics, others (indium: 0.21 g)	Manual dismantled for landfill	
Plastic light guide	1565	Polymethilmetacrylate (PMMA)	Manual dismantled for recycling	
Plastic foils	100	Plastics	Manual dismantled for recovery	
Fluorescent lamps (2)	8	Glass + various (Hg: 4 mg; rare earths – various: 5.8 mg)	Manual dismantled for mercury recovery	
Capacitors (n°2)	9	Various	Manual dismantled for landfill	
Cables	145	Various	Manual dismantled for recycling/recovery	
Fan	19	Plastics (various)	Manual dismantled and sorted (including post shredding separation)	
Speakers	196	Ferrous metals (70%) and plastics (unspecified)		
Screws	30	Iron/steel		
Total mass	7186			

some criteria for the considered EoL processes. This step is further subdivided in:

3.1.a Identification of key components (for hazardous substance). This approach is applied to identify product's parts that are relevant for their content of hazardous substances of the product.

3.1.b Identification of losses for the selected indices. 'Losses' occur when the design of the product is not optimized for the current EoL treatments (e.g. losses in terms of masses not reused/recycled/recovered). These losses can be calculated as difference of the performance of the analysed product when undergoing different EoL treatments or as difference of the performance of the product in comparison with best-case products (benchmarking[1]).

3.2 Identification of hot spots. The results of the previous steps (3.1 and 3.2) identified the key parts for some of the considered criteria. This new step combines these results to identify hot spots at the product level.

Step 4. Identification of potentially relevant measures at the product level. Once hot spots have been identified, it is performed an analysis to identify potential product measures that could contribute to the improvement of the product performances (e.g. contributing to the reduction of the losses and the improvement of EoL performances). Measures are afterwards tested to assess if and how they can produce, some relevant lifecycle benefits at the case-study level. Table 1 illustrates some exemplary types of measures for EuP.

Step 5. Assessment of policy measures at the 'product group' level. The last step consists in the extension of the analysis from the 'case-study' level to the 'product group' level. Performances of different products (representative of the considered product category) are assessed for the considered EoL scenario(s). Estimated environmental benefits at the product level are afterwards multiplied by the flows of different product within the considered economy. Results are then normalized[2] to assess their significance.

Table 3
Information about the case-study LCD-TV.

Life cycle stage	Assumptions and data sources
Production of materials	- Bill of Materials – BoM (as in Table 2); - Composition of Printed Circuit boards adapted from (Mohite, 2005; ADEME, 2008; UNEP, 2011); - Life Cycle Inventory data of materials from (Ecoinvent, 2007; EC, 2010d; PE, 2011; BUWAL, 1996; Plastics Europe, 2011); - Impacts of packaging not considered
Manufacturing	- Energy consumption for the manufacturing of the PCB estimated from (Williams, 2004); - Energy consumption for the manufacturing and assembly not available (assumed not relevant); - Transport of raw materials to production plant not consider (estimated not relevant);
Use	- Product life: 10 years; use: 4 h/day on-mode, 20 h/day standby (off-mode).(IZM, 2007); - Average energy consumption in different modes: on-mode (40 W/h), standby (0.3 W/h); - Inventory of transport from (EC, 2010d);
End-of-Life	- Inventory data about the landfill of metals, plastics and inert from (EC, 2010d). - Inventory data of recycled materials from (BUWAL, 1996; Ecoinvent, 2007; PE, 2011); inventory data of recycled plastics assumed 20% of primary ones; - Impacts due to the sorting of materials are neglected.

3. Definition of indices for the assessment of selected criteria

The following sections illustrate a set of qualitative and/or qualitative indices for criteria selected in the REAPro method.

[1] It is assumed that the 'benchmark product' is a product specifically designed to have optimized values of the RRR indices.

[2] Results can be normalized to various reference values as: impacts of the whole product group, and/or the impacts of an economic macro-sector (e.g. impacts of ErP), and/or impacts of a geographic area (e.g. impact at the EU level).

3.1. Reusability/Recyclability/Recoverability

Concerning the Reusability/Recyclability/Recoverability (RRR), two indexes have been defined as following.

3.1.1. Reusability/Recyclability/Recoverability (RRR) rates (in mass)

The three RRR indices in terms of mass rates can be calculated as:

$$\mathrm{RRR} = \frac{\sum_{i=1}^{P} m_i \cdot X_{\mathrm{RRR},i}}{m} \cdot 100 \quad [\%] \tag{1}$$

where:

- RRR = Reusability/Recyclability/Recoverability rates [%];
- m_i = mass of the ith part of the product [kg];
- $X_{\mathrm{RRR},i}$ = Rates of the ith part of the product that is potentially reusable/recyclable/recoverable (X_{reuse}; X_{recyc} and X_{recov} respectively) [%];
- P = number of parts of the product [dimensionless];
- m = total product's mass [kg].

Formula 1 summarizes the structure of the three indices. Their structure is consistent with the formulas of the IEC/TR 62635 (IEC, 2012). However, unlike the IEC/TR, it is proposed to introduce a separate index for the reusability. This difference makes the indices coherent with the principles of the "waste hierarchy" and with the objective of optimizing the use of different strategies (EU, 2008).

According to the IEC/TR 62635 the X_{RRR} rates are referred to a representative EoL scenario for the considered product. The EoL scenario shall be developed on the basis of information from manufacturers and recyclers, and information on the scientific literature about the EoL treatments.

It is proposed to identify reusable parts of the product according to the following criteria defined by (IEC, 2012):

a) "*It is possible to separate the part from the product while maintaining the part or component's functional integrity*".
b) *and "the manufacturer can provide evidence that a commercial reuse and refurbishment system has been established for that part that take into consideration regulation and market expectations"*.

Recyclable and recoverable parts should be identified according to the current representative EoL treatments for the product. The IEC/TR 62635 provides some exemplary data for the recycling and recovery rates of parts generally included in EEE (IEC, 2012).

It is highlighted that the EoL scenario has a geographical and temporal representativeness. It implies that the scenarios can vary due to the considered geographical area or the time frame of the analysis. It is recommended to vary the EoL scenario within a sensitivity analysis of the initial assumptions, including, when relevant, also the analysis of potential future scenarios.

3.1.2. Reusability/Recyclability/Recoverability (RRR) rates (in terms of environmental impacts/benefits)

The prioritization of resources can be performed on the basis of potential environmental benefits related to the potential reuse/recycling/recovery of the product's parts. A set of environmental indices have been developed, named 'RRR Benefit Rates'. These indices are based on the RRR rates previously introduced with the inclusion of the lifecycle impacts about: production of virgin materials, manufacturing of the product, recycling and production of secondary materials, transport and disposal. The RRR Benefit rates indices can be calculated as:

$$R_{\mathrm{use}_n} = \frac{\sum_{i=1}^{P} m_{\mathrm{reuse}_i} \cdot X_{\mathrm{reuse},i} \cdot \left(V_{\mathrm{reuse}_{n,i}} + M_{\mathrm{reuse}_{n,i}} + D_{\mathrm{reuse}_{n,i}} - T_{\mathrm{reuse}_{n,i}}\right)}{V_n + M_n + U_n + D_n} \cdot 100 \quad [\%] \tag{2}$$

$$R_{\mathrm{cyc},n} = \frac{\sum_{i=1}^{P} \left(m_{\mathrm{recyc},i} \cdot X_{\mathrm{recyc}_i} \cdot D_{n,i}\right) + \sum_{i=1}^{P} \left[m_{\mathrm{reyc},i} \cdot X_{\mathrm{recyc}_i} \cdot \left(k_i \cdot V^*_{n,i} - R_{n,i}\right)\right]}{V_n + M_n + U_n + D_n} \cdot 100 \quad [\%] \tag{3}$$

$$\mathrm{ER}_{\mathrm{cov},n} = \frac{\left(\eta_{\mathrm{el}} \cdot \sum_{i=1}^{P} X_{\mathrm{recov}_i} \cdot m_{\mathrm{recov},i} \cdot \mathrm{HV}_i\right) \cdot \mathrm{El}_n + \left(\eta_{\mathrm{heat}} \cdot \sum_{i=1}^{P} X_{\mathrm{recov}_i} \cdot m_{\mathrm{recov},i} \cdot \mathrm{HV}_i\right) \cdot \mathrm{Heat}_n - \sum_{i=1}^{P} m_{\mathrm{recov},i} \cdot I_{i,n}}{V_n + M_n + U_n + D_n} \cdot 100 \quad [\%] \tag{4}$$

Where symbols previously not introduced are:

- $R_{\mathrm{use,n}}$ = 'Reusability benefit' rate (for the "n" impact category) [%];
- $R_{\mathrm{cyc,n}}$ = 'Recyclability benefit' rate (for the "n" impact category) [%];
- $\mathrm{ER}_{\mathrm{cov,n}}$ = 'Energy recoverability benefit' rate (for the "n" impact category) [%];
- $m_{\mathrm{reuse,i}}$ = mass of the ith reusable part of the product [kg];
- $m_{\mathrm{recyc},i}$ = mass of the ith recyclable part of the product [kg];
- $m_{\mathrm{recov},i}$ = mass of the ith recoverable part of the product [kg];
- $V_{\mathrm{reuse},n,i}$; $M_{\mathrm{reuse},n,i}$; $D_{\mathrm{reuse},n,i}$ = impacts (for the "n" impact category) due to the production of virgin materials, manufacturing and disposal of the 'ith' reusable part [unit/kg][3];
- $T_{\mathrm{reuse},i}$ = impacts (for the "nth" impact category) due to the treatments for reuse of the 'ith' reusable part [unit/kg];
- V_n, M_n, U_n, D_n = impacts (for the "nth" impact category) due to the production of virgin materials, manufacturing, use and disposal of the product [unit];
- $V^*_{n,i}$ = impact (for the "nth" impact category) due to the production (as virgin) of the material assumed to be substituted by the ith recyclable material of the product [unit/kg];
- $R_{n,i}$ = impact (for the "nth" impact category) due to the recycling of the ith recyclable part [unit/kg];

[3] The unit of measure depends on the selected impact category.

- k_i = downcycling factor [dimensionless];
- η_{el} and η_{heat} = average energy efficiency for the production, respectively, of electricity and heat from the energy recovery processes[4] [%];
- HV_i = Heating value of the ith material that is energy recoverable [MJ/kg];
- El_n and $Heat_n$ = Impact (for the "nth" impact category) due to the average production of electricity and heat respectively for the considered geographical context [unit/MJ];
- $I_{i,n}$ = Impact (for the "nth" impact category) for the energy recovery of the ith material [unit/kg];

The calculation of benefits is based on the assumption that avoided (or reused/recycled/recovered) materials will imply a reduced use of resources (and consequently a reduction of impacts) in other systems (Ekvall and Finnveden, 2001). Similar indices have been discussed in the scientific literature, as for example by (Huisman et al., 2003; Mathieux et al., 2008) concerning the recyclability. However compared to the literature, the indices here proposed differ for the accounting of benefits due to RRR of product's parts and for the denominator used in the formulas. (which represents the lifecycle impact of the product, for the considered "nth" impact category).

The changes of the inherent properties of materials in subsequent reuse/recycling process is a key issue for the environmental analysis of the products (ISO, 2006a). These changes have been considered in the index for Recyclability benefit with the introduction of a specific downcycling factor '*k*'. It takes into account the factors that "depreciate" the quality of the materials after their recycling (including e.g. contamination among different materials and loss of physical performances due to the treatments) (EC, 2010a). The downcycling factor can be referred to economic or physical parameters, although the scientific community did not identify a preferred alternative yet. The analysis of the downcycling is potentially complex and still limited in the scientific literature. In particular, there are no evidences about the use of downcycling factors related to physical properties, while some factors relate to the economic values of primary and secondary materials (Villalba et al., 2002).

3.2. Recycled content

Concerning the Recycled content, two indexes have been defined as following.

3.2.1. Recycled content rate (in mass)

The method for the calculation of the recycled content is substantially consolidated and standardised in the scientific literature (e.g. by (ISO, 1999; CEN, 2007). The content of the recycled materials in a product can be assessed with the following index:

$$R_{Content} = \frac{\sum_{i=1}^{P} m_{r,i}}{m} \cdot 100 \quad [\%] \tag{5}$$

Where symbols previously not introduced are:

- $R_{content}$ = recycled content of the product [%]
- $m_{r,i}$ = mass of recycled material in the ith part [kg]

The index can refer to different types of waste (e.g. 'pre-consumers' waste, 'post-consumers' waste or both) and to different materials (recycled content related to plastics).

[4] The values of the energy efficiency factors depend on the characteristics of the plant for the energy recovery of the product.

It is highlighted that pre-consumers materials (e.g. material diverted from the waste stream during the manufacturing process) have generally a higher 'quality' in terms of homogeneity and purity, which increase their 'attractiveness' for recycling. On the other side, recycling of post-consumer waste needs to be encouraged because post-consumers materials are those affected by lager downcycling when recycled (EC, 2010a). Therefore, the analysis of the recycled content in the REAPro method focuses only on post-consumer materials with low values when recycled (e.g. plastics).

3.2.2. Recycled content rate (in terms of environmental impacts/benefits)

Similarly tor RRR and RRR Benefits indices, it is possible to define the "Recycled content benefit" rate. This index is originally developed and it calculates, in a lifecycle perspective, the environmental benefits (for certain impact categories) that can be achieved by introducing some recycled materials during the manufacturing of the product. It is defined as:

$$RCB_n = \frac{\sum_{i=1}^{K} m_{r,i} \cdot \left(V_{n,i} - R^*_{n,i}\right)}{V_n + M_n + U_n + D_n} \cdot 100 \quad [\%] \tag{6}$$

Where symbols previously not introduced are:

- RCB_n = recycled content benefit rate of the product (for the "nth" impact category) [%]
- $R^*_{n,i}$ = impact (for the "nth" impact category) of the recycled material used for the ith product's part [unit/kg];
- $m_{r,i}$ = mass of the ith recycled material in the product [kg];
- $V_{n,i}$ = impact (for the "nth" impact category) due to the production (as virgin) of the material substituted by the ith recyclable material of the product [unit/kg].

3.3. Use of hazardous substances

The use of hazardous substances (HS) can largely affect the EoL treatments of products. However this influence is related to several issues including: safety (potential risks related to workers during the waste treatments), environmental impacts (due e.g. to releases of substances in the environment) and legislation in force (including obligations for the extraction and specific treatments of some components embodying the HS). Therefore the use of HS cannot be translated into a simple formula, as performed for the previous parameters. The use of HS can be assessed qualitatively, according to the following steps:

Step 1. Definition of the set of substances to be considered for the analysis. The set shall include regulated substances (e.g. by the REACH Regulation, the RoHS and the WEEE Directives) and other relevant substances (as identified according to feedback from e.g. manufacturers, recyclers, standards).
Step 2. Identification of parts of the product that contain the considered substances (quantities and types).
Step 3. Identification of current treatments for the EoL of these parts. It is necessary to identify the recovery treatments that the components will undergo at EoL and potential related impacts for workers and the environment.
Step 4. Identification of hot spots (i.e. product's parts that contain some HS that are critical for the identified EoL treatments).

It is highlighted that some HS could be treated into specialized plants without representing a real obstacle for the EoL processes. In this case the parts containing the HS are not identified as hot spots.

4. Analysis of a case-study product: LCD-TV

The following sections illustrate the application of the REAPro method to a case-study.

4.1. Product's selection and characterization

The selected case-study is a LCD-TV (20.1 inches) with a Cold Cathode Fluorescent Lamp (CCFL) backlight system.

Data about the BoM of the product have been collected in a WEEE recycling plant. Data about the dismantling and the recycling treatments have been collected from various recyclers. Additional information about the composition of some parts has been derived from the scientific literature, in particular:

- the composition of Printed Circuit Boards is estimated from (Mohite, 2005) while content of precious metals in the boards is estimated from (ADEME, 2008; UNEP, 2013)
- the composition of LCD screen estimated from (Kim et al., 2009; Lee and Cooper, 2008); content of indium in the screen is estimated from (Li et al., 2009);
- the content of mercury in CCFL is estimated from (IZM, 2007), while their content of rare earth is estimated from (Rabah, 2008).
- Product's information is illustrated in Table 2, including the description of parts (BoM).

A complete description of the product is provided in (Ardente and Mathieux, 2012). Compared to this document the present case-study differs for the mass and material of some the plastic frames (high impact polystyrene – HI-PS, with 50% of flame retardant) (Table 2) and for the energy consumption during the use phase (Table 3).

4.2. Definition of EoL scenarios

Table 2 illustrates the EoL treatments of the product, based on two EoL scenarios (set in accordance to (IEC, 2012) and based on information collected from 4 representative European recycling plants):

- EoL scenario 1: “Manual dismantling” scenario: the product is fully manually dismantled to separate potential hazardous components (e.g. CCFL, LCD screen, Printed Circuit Boards, capacitors) and other parts (mainly metals and plastics) for further treatments.
- EoL scenario 2: “Mechanical Treatment (Shredding)” scenario: the product is mainly treated by special shredders (in a controlled environment) to separate mercury and avoid contamination of other parts. Shredded parts are subsequently mechanically sorted for recycling/recovery. Before the shredding, recyclers also implement minor dismantling operations for some key components, when economically viable or required by legislation.

4.3. Assumptions and data used for the calculation of the indices

This section discusses some details for the calculation of the indices in Section 3 for the LCD-TV case-study.

Some indices (‘RRR benefits’ and ‘Recycled content benefit’ rates) require the assessment of the lifecycle impacts of the product. These impacts have been calculated according to the assumptions in Table 3.

Concerning the reuse, no evidences of reusable part have been observed during the survey of the recycling plants. Potential reuse of TV's parts has been under investigation in the scientific literature (Kopace, 2008; Letcher et al., 2010). Reasons for current limited reuses can be explained by the potential counterproductive effect to energy efficiency of reusing old components (UNU, 2007). Moreover, LCD-TV technologies are currently quickly changing and the reuse of components (especially electronics) can be not compatible with the technological developments.

Recyclability and recoverability (in mass) have been calculated according to Formula 1, based on average recycling rates as provided by IEC (2012).

The Recyclability benefit rates have been calculated for a set of representative impact categories (Table 4). The selection of the impact categories is based on ILCD Handbook recommendations (EC, 2010a) and on the availability of characterization factors in the Gabi 4.0 LCA software (PE, 2011). Compared to the previous index, the Recyclability benefit rate focuses on those materials that are relevant in terms of lifecycle environmental impacts, although not relevant in mass. In the LCD-TV this is the case of precious metals in printed circuit boards (PCB).

According to various authors (Chancerel et al., 2009; Meskers et al., 2009) the separation of PCB after shredding can cause large losses of precious metals. These, in fact, are contained in conjunctions or contacts and are dispersed in the air when circuit boards and other electronic components are shredded. For example, according to Chancerel et al. (2009) and Meskers et al. (2009), the recycling rates of silver can vary from 11% to 92% in the “mechanical treatment” and the “dismantling” EoL scenario respectively; analogously the recycling rates of gold can vary from 25.6% to 97%. These percentages have been implemented in the method for the calculation of the Recyclability benefit rates (Formula 3).

Furthermore, for the calculation of the Recyclability benefit rates it has been detected a general lack of lifecycle inventory data about recycled plastics. Impacts of recycled plastics have been roughly estimated on the basis of data available concerning recycled HI-PS (Ross and Evans, 2002). Finally, in the analysis of the case-study downcycling of materials has been not included, due to the lack of information on the loss of quality of recycled materials.

The analysis of the Energy Recoverability benefits considers the potential benefits that can be achieved when the feedstock energy embodied in the product's parts is recovered in the incineration plants (for the production of electricity and heat). In the calculation it has been assumed that the energy recovered substitutes the electricity and heat produced according to the average European energy mix (EC, 2010d). Also impacts for incineration of various materials are referred to (EC, 2010d). The average energy conversion factors (η_{el} and η_{heat} of Formula 4) are assumed 0.3 and 0.6 respectively. Average heating values of plastics are derived from technical manuals and/or website. The Energy Recoverability benefit rate has been calculated only for the “Abiotic Depletion – fossil” – impact category, being the impact category mainly influenced by the energy recovery processes.

Concerning the recycled content of plastics in the LCD-TV, no evidence of recycled materials employed for the manufacturing of the products was found. The recycled content rate for plastics is assumed null. However a further analysis of potential variation of the lifecycle impacts of the product due to the use of recycled materials is presented in the following Section 4.4.5.

Finally the analysis of HS identified substances that could interfere with the EoL treatments of the product. The analysis has been based on the current European legislation (EU, 2011; EU, 2012), on feedback from recyclers and on information available in the scientific literature.

4.4. Results and identification of product's hot spots

The indices introduced in Section 3 (Table 4) have been calculated according to the two EoL scenarios presented in Table 2. These

Table 4
Results of the resource efficiency indices.

Indexes for resource efficiency			EoL scenarios	
			Dismantling	Mechanical treatment
Reusability	(in mass)	[%]	0%	0%
Recyclability	(in mass)	[%]	75.3%	34.5%
Recoverability	(in mass)	[%]	79.7%	49.0%
Reusability benefit	(for all impact categories)	[%]	0%	0%
Recyclability benefit	(Climate change)	[%]	6.6%	2.7%
	(Acidification)	[%]	19.5%	5.9%
	(Photochemical oxidant)	[%]	12.7%	4.2%
	(Ozone depletion)	[%]	1.2%	0.8%
	(Respiratory effects)	[%]	18.6%	6.2%
	(Eutrophication freshwater)	[%]	15.9%	5.5%
	(Eutrophication marine)	[%]	10.9%	3.5%
	(Human toxicity)	[%]	65.7%	32.1%
	(Aquatic Ecotoxicity)	[%]	47.9%	17.9%
	(Terrestric ecotoxicity)	[%]	50.4%	23.7%
	(Abiotic Depl. – el.)	[%]	95.2%	24.8%
	(Abiotic Depl. – fossil)	[%]	8.3%	2.5%
Energy Recoverability benefit	(Abiotic Depl. – fossil)	[%]	2.8%	1.9%
Recycled content	(in mass)	[%]	0%	0%
Recycled content benefit	(Abiotic Depl. – fossil)	[%]	0%	0%
Use of hazardous substances			○ CCFL (containing mercury) ○ LCD, PCB and Capacitors (for the content of various hazardous substances)	○ CCFL (containing mercury) need shredding in a controlled environment ○ LCD, PCB and Capacitors (for the content of hazardous substances) need to be separated after shredding, in compliance with legislation

results have been used to identify product's hot spots, as illustrated in the following sections.

4.4.1. Hot spots for reusability (in mass and environmentally based)

According to the previous analysis, no part of LCD-TV is currently reused, both for economic and technical reasons. Although all the product's parts are potentially reusable, current EoL treatments do not allow separation for reuse. Therefore, no hot spot for the reuse (both in terms of mass and environmental benefits) is identified for the case-study.

4.4.2. Hot spots for recyclability (in mass)

The analysis of the recyclability (in mass) showed a large discrepancy between the results in the two EoL scenarios. This is due to the optimized processes in the “dismantling” scenario for the sorting of recyclable parts, mainly PCB and other electronics, large plastic fractions (HI-PS frames and the Polymethilmetacrylate – PMMA – board). On the other hand, the Recyclability rate in the “mechanical treatment” scenario is much lower. The shredding with mechanical sorting is, in fact, characterized by lower recycling percentages for common metals and, especially, for precious metals and plastic parts. For example, according to (IEC, 2012), the recyclability of PMMA after shredding is null.

Large plastic parts (HI-PS and PMMA board, which amount to about 40% of the TV) are therefore hot spots for the recyclability (in mass). These parts are, in fact, largely lost during the mechanical treatments.

A large loss of materials (around 7% in mass of the TV) is also due to the treatment of the LCD screen. This part is also identified as a product's hot spot for the recyclability (in mass). According to recyclers, LCD screens are currently landfilled or, in some cases, temporary stored in prevision of the availability of future recycling technologies. However, LCD screens can be relevant for their content of indium. Small amounts of indium are currently recycled due to lack of infrastructures and low prices of the metal (USGS, 2012). However, exemplary recycling processes for indium are currently under research and development (see, for example, Takahashi et al. (2009)).

4.4.3. Hot spots for recyclability (environmentally based)

The recyclability benefit index allows to identify the losses of potential environmental benefits due to the different recycling treatment of materials. The results for the case-study confirmed the large discrepancy between the two EoL scenarios. The losses have been calculated as following:

$$\mathrm{Loss}_n = \left(R_{\mathrm{cyc},n,1} - R_{\mathrm{cyc},n,2}\right) \quad [\%] \tag{7}$$

Where symbols previously not introduced are:

- Loss_n = Loss of potential environmental benefits (for the nth impact category) due to difference in treatments [%]
- $R_{\mathrm{cyc},n,1}$ = Recyclability benefit rate (for the nth impact category) in EoL scenario 1 [%];
- $R_{\mathrm{cyc},n,2}$ = Recyclability benefit rate (for the nth impact category) in EoL scenario 2 [%].

Large losses in the two scenarios occur for almost all the considered impact categories. In particular the most significant loss

Table 5
Recycled content benefit index for the LCD-TV (Abiotic Depletion - fossil).

Percentage of recycled materials in large plastic parts [%]	Recycled content (in mass) [%]	Recycled content benefits (for Abiotic Depletion potential- fossil) [%]
0%	0%	0%
20%	4.2%	0.4%
60%	12.6%	1.3%
100%	21.0%	2.2%

Table 6
Summary of product's hot spots.

Criteria	Hot spots
Reusability (in mass)	(none)
Recyclability (in mass)	LCD; large plastic parts (HI-PS frames; PMMA board)
Recoverability (in mass)	(none)
Reusability benefit (environmentally based)	(none)
Recyclability benefit (environmentally based)	PCB; PMMA board
Recoverability benefit (environmentally based)	(none)
Recycled content	Large plastic parts (HI-PS frames;
Recycled content benefit (environmentally based)	(none)
Use of hazardous substances (HS)	CCFL; LCD; PCB

(over 70%) is related to the impact category "Abiotic Depletion – element". Other relevant losses (from 20% to 30%) regard also the "Human Toxicity", "Freshwater Aquatic Ecotoxicity" and "Terrestric Ecotoxicity".

These losses are mainly due to the lower recycling rates of precious metals (gold, silver and platinum group metals) in PCB in the Scenario 2 (largely dispersed in the dusts during the shredding). On the other hand, the manual dismantling optimizes the separation of PCB and the consequent recycling precious metals.

PCB are therefore hot spots of the TV for the Recyclability benefits.

The PMMA board is another hot spot. The loss of the PMMA during the mechanical treatments causes, in fact, a loss of benefits from 2% to 4% for various impact categories as "Abiotic Depletion – fossil", "Acidification Potential", "Eutrophication Potential" and "Photochemical Ozone Creation Potential".

4.4.4. Hot spots for recoverability (in mass and environmentally based)

The Recoverability (in mass) has similar results to the Recyclability in mass. Manual dismantling scenario generally allows larger recovery of not recyclable fractions. The mechanical treatments scenario is, instead, affected by larger losses of plastics in the shredding residuals, which are only partially recovered.

Concerning the Energy Recoverability benefit, the manual dismantling scenario grants better performances, due to the selective sorting of plastics. In terms of "Abiotic Depletion – fossil" impact category, the energy recovery of plastics of the products allows a benefits of 2.8% of the lifecycle impact of the product. The loss of benefits during the treatments in the two scenarios is however limited (less than 0.7%). Furthermore, according to the European waste hierarchy, recovery of products has low priority. Therefore, no product's hot spot is identified as relevant for the Recoverability criteria.

4.4.5. Hot spots for recycled content (in mass and environmentally based)

This section analyses if the use of recycled materials in the manufacturing of the TV could produce relevant benefits. The analysis has been targeted to large plastic parts, as HI-PS parts heavier than 200 g (back cover, front cover and support).

According to studies in the literature (WRAP, 2010), primary HI-PS used for the frames of EEEs can be substituted by recycled materials without interfering with its functionality. For example, WRAP, 2010 demonstrated that use of recycled HI-PS plastics up to 90% in some imaging equipment allows the same technical requirements of virgin plastics. It is assumed that also LCD-TV can use recycled plastics.

By changing the content of recycled HI-PS in large plastic parts from 0% to 100%, the Recycled content index (in mass, Formula 5) of the product varies from 2% to 21% (Table 5). Large plastics parts are considered as hot spots for the Recycled content in mass.

Subsequently, the potential environmental benefits associated to the use of recycled materials have been calculated according to Formula 6. The calculation has been done for the "Abiotic Depletion – fossil" impact category (assumed as the most relevant for this criterion). The impacts of recycled HI-PS refer to Ross and Evans (2002).

The analysis demonstrates that, for example, a 20% recycled content of HI-PS can allow a 0.4% saving of the overall lifecycle "Abiotic Depletion – fossil". A percentage of 60% of recycled HI-PS would allow a 1.3% benefit for the same impact category. Being these benefits much lower than befits achievable through e.g. the reduction of the consumption in the use phase (see e.g. (IZM, 2007)), it is concluded that there are no product's hot spots relevant for the Recycled content benefit criterion.

4.4.6. Hot spots for the use of hazardous substances

According to recyclers, the main criticality for HS in LCD-TV is represented by the mercury in CCFL. This mercury is potentially dangerous if spread during both the dismantling scenario (STENA, 2010) and the shredding scenario (McDonnell and Williams, 2010).

In particular, in the dismantling scenario, the major risk is represented by the breakage of the lamps during the dismantling, with potential high impacts for the safety of workers and the environment. Risks could be minimized by a careful design of the lamps (and their casing) to facilitate their extraction. The mechanical treatment scenario allows to minimize the risks for the workers but, on the other hand, it can contaminate other recyclable parts with mercury residues. Special shredders in a controlled environment are currently under development (STENA, 2010). CCFL are therefore assessed as hot spots for HS.

Table 7
Examples of product measures related to various product policies.

Types of product policy	Measure 1	Measure 2	Measure 3
Mandatory policy (threshold)	The time for the dismantling of key components (LCD, PCB, PMMA board and CCFL) shall not exceed 240 s	–	–
Mandatory policy (declaration)	–	The recycled content of plastic frames (>200 g) shall be declared	Content of indium in LCD screen shall be declared
Voluntary policy (including mandatory requirements)	–	The recycled content of plastic frames (>200 g) shall exceed 20% (in mass).	–
Voluntary approach	The time for the dismantling key components (LCD, PCB, PMMA board and CCFL) should be declared. Continuous improvement should be demonstrated.	The recycled content of plastic frames (>200 g) should be declared. Continuous improvement should be demonstrated.	Content of indium in LCD screen should be declared

Table 8
Benefits (in terms of additional recyclable masses) for the treatment of the LCD-TV in the 'manual dismantling' instead than in the 'mechanical treatments' scenario.

Additional masses of recycled materials [g/TV]	Copper (PCB and cables)	Silver (in PCB)	Gold (in PCB)	Palladium (in PCB)	Platinum (in PCB)	Steel (various parts)	Aluminium (various parts)	PMMA (board)	HI-PS (frames)
Measure $n°1$	52.2	0.43	0.15	0.03	0.002	18.7	15.3	1471.1	792.8

Other potential hot spots for HS are the LCD screen, PCB and capacitors. According to current legislation (EU, 2011; EU, 2012), these parts have to be removed from the TV and separately collected. According to the EoL scenarios, this separation can be performed manually (by dismantling and sorting) or after the shredding (by mechanical sorting systems or hand-picking). LCD screen and PCB are considered as hot spots for HS. Instead, according to communications from manufacturers, current capacitors are now free of polychlorinated biphenyl and, therefore, these parts are not considered as relevant for the analysis.

4.4.7. Summary of identified hot spots for the selected criteria

A summary of the analysis of criteria and hot spots for the case-study is illustrated in Table 6.

4.5. Identification and assessment of product's measures for the improvement of resource efficiency

This step of the analysis focuses on the identification of product's measures to improve the resource efficiency of the product for each considered criterion.

These measures could be applied via mandatory requirements (enforced by the current legislation as, for example, the set of minimum thresholds according to the (EU, 2009) or the declaration of information (EU, 2009; EU, 2010)), via voluntary approaches based on mandatory requirements (environmental labelling systems (EC, 2011b)) or via voluntary actions (as environmental claims and declarations (ISO, 1999)). A summary of types of potential measures for EuP/ErP has been presented in Table 1.

According to the analysis during the previous steps (Table 6), it is observed that some product's parts are relevant for one or more studied resource efficiency criteria and, in particular:

- PCB are hot spots for Recyclability benefits and the content of HS. Selective sorting of these parts is therefore desirable but it is hampered by some difficulties, mainly the large time (and subsequent costs) for the manual dismantling. Furthermore, the mechanical treatment scenario causes large losses of relevant materials contained in PCB. Therefore, manual dismantling of PCB should be improved (e.g. by thresholds for the time for dismantling).
- LCD screen is a hot spot for Recyclability (in mass) and the content of HS. Screens are currently landfilled, causing large environmental burdens (Leet Socolof et al., 2005; Robinson, 2009) and also the loss of relevant materials (e.g. indium). Although not fully established in all the countries, there exist examples of economically viable technologies for the treatments of this component (as for example in Japan (Hong et al., 2010)). According to recyclers, the recycling of LCD screens could be promoted by measures to improve the dismantlability of the TV and by the communication of some key information, as the content of indium (Ardente and Mathieux, 2012). These measures could contribute to the creation of concentrated waste, which can be the basis for the development of large-scale economically viable technologies for the recycling of indium.
- Large HI-PS parts are hot spots for Recyclability (in mass) and Recycled content (in mass). The marking of plastic parts is a possible measure to improve their sorting during the manual dismantling by recyclers. The PMMA board is a hot spot for Recyclability (in mass and environmental benefits). PMMA is in fact lost when the TV is shredded. Analogously to LCD screen and PCB, measures to support dismantlability of the PMMA board could support manual and mechanical EoL treatments. Marking of PMMA board should be avoided to not compromise its transparency.
- CCFL are hot spots for the content of mercury. The treatment of mercury represents one of the biggest difficulties faced in the treatment of LCD-TV. Measures should be set in order to improve the design for disassembly of CCFL, supporting the 'dismantling' scenario and minor dismantling operations before the 'mechanical treatments'.

According to previous considerations, some exemplary measures are here proposed:

Measure $n°1$. "The time for the dismantling of product's key components (i.e. PCB, LCD screen, PMMA and CCFL) shall be less than 240 s[5]". This measure could be set via mandatory or voluntary requirements.
Measure $n°2$. "The recycled content of large plastic frames (>200 g) should be higher than 20%[6]". This measure could be set via voluntary requirements (e.g. Ecolabel).
Measure $n°3$. "Manufacturer should declare the content of indium in the LCD-TV". This measure could be set via mandatory and voluntary requirements (including environmental claims). The declaration should be in line with available standards (ISO, 1999).

It is important to highlight that these measures could be modified and adapted to different product policies, also in different stages.

For example, Measure $n°2$ could face some problems related to the technical feasibility (e.g. identification of parts suitable for recycled resins) and market feasibility (i.e. availability of recycled resin). Therefore measures on recycled content could be implemented through different stages: initially the declaration of the recycled content could be introduced in compulsory schemes while the setting of thresholds in voluntary labelling (e.g. EU Ecolabel); successively, declarations in compulsory schemes could be coupled with some lower thresholds (easier to be achieved), while higher thresholds could be set in voluntary labelling schemes (which generally identify the 'excellence' in the market). However, measures on the recycled content are also difficult to be verified. In fact the verification should be based on a documental verify (as for example the documentation to prove the traceability of input materials as suggested by available standards (CEN, 2007). For this

[5] This threshold is only exemplary and based on some measurements at the recycling plants. The setting of the threshold should be further discussed together with recyclers and manufacturers, and should be also adapted to LCD-TV with different dimensions and to automatic dismantling initiatives (when developed).

[6] This threshold is only exemplary and should be discussed with TV manufacturers and producers of recycled polymers.

Table 9
Estimated environmental benefits due to measure $n°1$.

Environmental impact category	Climate change	Acidification	Photochemical oxidant	Ozone depletion	Respiratory effects	Eutroph. freshwater
	kg $CO_{2\text{-eq.}}$	kg $SO_{2\text{-eq.}}$	kg $NMVOC_{\text{-eq.}}$	kg $CFC_{11\text{-eq.}}$	kg $PM_{10\text{-eq.}}$	kg $P_{\text{-eq.}}$
A. Estimated benefits	15.12	0.40	0.08	3.3E-07	0.08	0.011
B. Lifecycle impacts LCD-TV	397.4	3.5	1.0	8.8E-05	0.75	0.1
(A/B) [%]	3.8%	11.5%	7.8%	0.4%	10.5%	9.9%

Environmental impact category	Eutroph. marine	Human toxicirty	Acquatic Ecotoxicity	Terrestric ecotoxicity	Abiotic Depl. – element	Abiotic Depl. – fossil
	kg $N_{\text{-eq.}}$	kg $DCB_{\text{-eq.}}$	kg $DCB_{\text{-eq.}}$	kg $DCB_{\text{-eq.}}$	kg $Sb_{\text{-eq.}}$	MJ
A. Estimated benefits	0.022	26.43	0.87	0.26	0.009	241.92
B. Lifecycle impacts LCD-TV	0.3	116.8	3.1	1.2	0.0	4195.6
(A/B) [%]	7.3%	22.6%	28.2%	21.7%	71.6%	5.8%

reason, thresholds of the recycled content can be more difficult to be enforced in mandatory policies.

Thresholds of the time for disassembly of key parts could be enforced in both mandatory measures and voluntary measures (with more ambitious targets). This is based on the general idea that mandatory policies aims at cutting off low performance products, while voluntary policies aims at supporting the excellences. Examples of different measures adapted to different policies are illustrated in Table 7.

4.5.1. *Assessment of the potential environmental benefits at the case-study level*

According to communications from stakeholders (manufacturers, recyclers, NGOs), the full dismantling scenario is currently economically viable and extensively applied in the EU for the treatments of LCD-TVs (around 95% of masses) (Ardente and Mathieux, 2012). However there is plenty of evidence of technological progresses moving towards mechanical systems for the EoL treatments of LCD-TV, including open air shredders or 'encapsulated units' (i.e. sealed shredders operating in a controlled environment) (EMPA, 2011). It is estimated that the mechanical treatment scenario will be improved and further implemented in the EU in the next future, mostly because of the higher economic efficiency and reduced risks for the safety of workers (Ardente and Mathieux, 2012). The dismantling scenario will become not competitive, unless actions to support this scenario will be undertaken (HÅPLA, 2012). The previously discussed measures on dismantlability aim to provide this support.

The next step of the analysis consists in the calculation of potential environmental benefits related to the application of the proposed measures to the case-study.

Concerning the Measure $n°1$, it is assumed that thanks to the improved dismantlability of key parts, the LCD-TV would be treated according to the dismantling scenario instead than the mechanical treatment scenario. The benefits are calculated in terms of masses of additional recyclable materials (Table 8) by comparing the recycling yields of the two EoL scenarios. Successively, the related lifecycle environmental benefits (Table 9) are estimated and compared to the lifecycle impacts of the product. It is possible to observe that the larger benefits concern the "Abiotic Depletion – element" impact category. Benefits related to other categories (including "Human toxicity", "Terrestric Ecotoxicity" and "Aquatic Ecotoxicity") are also relevant.

Concerning the Measure $n°2$, the manufacturing of large HI-PS frames with a recycled content of minimum 20% would have the effect of introducing around 300 g of recycled plastics in the product (i.e. having a recycled content in the product of about 4% in mass). In this case the lifecycle "Abiotic Depletion – fossil" of the LCD-TV would decrease of about 0.4% (see Table 5).

Finally, it is assumed that the Measure $n°3$ would promote the recycling of indium in LCD-TV. It is estimated that up to 90% of indium can be potentially recycled when the LCD screen is properly separated (Boeni et al., 2012). This corresponds to about 0.2 g of recyclable indium from the case-study TV. Environmental benefits related to this amount have been not estimated due to the unavailability of life cycle inventory data about the recycling process of indium from LCD screens.

4.5.2. *Assessment of product's measures at the 'product group' level*

The last part of the analysis consists in the calculation of the benefits of the measures at the product group level for the EU-27 geographical context.

The first step is represented by the estimation of the number of products (for the considered product group) potentially involved by the measures within the considered geographic context. The previous sections analysed a 20″ LCD-TV (with a mass of 7.1 kg). However, televisions in the market have different sizes and masses. It is here assumed that benefits per device can vary proportionally to the overall mass. Therefore the annual number of LCD-TV put on the market in the EU-27 has been estimated to be equivalent to about thirty-four millions of 20″ TVs[7].

As previously discussed, the dismantling scenario is currently adopted for the treatment of the large majority of LCD-TV waste, but the mechanical treatments will largely grow in the next future, becoming the most common EoL scenario (Ardente and Mathieux, 2012). However, this change would imply lower recycling rates.

For the assessment of the benefits of the previous Measure $n°1$, it is assumed that this could contribute in the future to maintain the dismantling scenario still competitive and preferable compared to the mechanical treatments due to: reduction of the manpower costs for dismantling; increase of the mass and quality of recyclable materials with consequent larger recycling yields and incomes; reduction of the risks of contamination of recyclable materials by hazardous substances.

Being not possible to establish how the proposed measure could exactly influence the evolution of EoL treatments, a scenario analysis has been introduced. In particular, it is assumed that, thanks to application of the Measure $n°1$ (on the improved dismantlability) as a compulsory requirement for all LCD-TVs, from 20% (Scenario 1.a) to 40% (Scenario 1.b) of the waste LCD-TV will be still manually dismantled instead than being shredded. Benefits in terms of additional recycled masses and reduction of life cycle impacts have been (Table 10).

Thanks to the application of Measure $n°2$ to voluntary schemes (e.g. the EU Ecolabel), it is estimated that a certain number of television, from 10% (scenario 2.a) to 20% (scenario 2.b), in the

[7] This value is based on the estimated figures of TV sold in 2010, according to (IZM, 2007), and scaled proportionally to the masses and shares of LCD-TV of different sizes. Details of the calculation are provided by Ardente and Mathieux (2012).

Table 10
Potential Environmental benefits of measure at the product group level.

Scenario[a]	Environmental benefits	Climate change	Acidification	Photochemical oxidant	Ozone depletion	Respiratory effects	Eutrophication freshwater	Eutrophication marine	Human toxicity	Aquatic Ecotoxicity	Terrestric ecotoxicity	Abiotic Depl. - element	Abiotic Depl.- fossil
		GWP	AP	POFP	ODP	PMFP	FEP	MEP	HTP	FAETP	TETP	ADP el.	ADP fossil
		kg $CO_{2\text{-eq.}}$	kg $SO_{2\text{-eq.}}$	kg $NMVOC_{\text{-eq.}}$	kg $CFC11_{\text{-eq.}}$	kg $PM10_{\text{-eq.}}$	kg $P_{\text{-eq.}}$	kg $N_{\text{-eq.}}$	kg 1,4-DCB	kg $DCB_{\text{-eq.}}$	kg $DCB_{\text{-eq.}}$	kg $Sb_{\text{-eq.}}$	MJ
1.a	Value	1.0E+08	3.1E+06	5.4E+05	2.1E+00	6.0E+05	7.6E+04	1.4E+05	1.8E+08	5.8E+06	1.7E+06	6.3E+04	1.6E+09
	Normalized	0.7%	2.6%	1.6%	0.1%	2.3%	1.9%	1.4%	4.5%	5.5%	4.2%	14.0%	1.1%
1.b	Value	2.0E+08	6.2E+06	1.1E+06	4.1E+00	1.2E+06	1.5E+05	2.9E+05	3.6E+08	1.2E+07	3.4E+06	1.3E+05	3.2E+09
	Normalized	1.5%	5.2%	3.2%	0.1%	4.7%	3.8%	2.8%	9.0%	11.0%	8.4%	28.0%	2.3%
2.a	Value												6.3E+07
	Normalized												0.04%
2.b	Value												1.3E+08
	Normalized												0.1%

[a] Detail of the scenarios: 1.a) dismantlability in mandatory policies (20% of waste TV affected); 1.b) dismantlability in mandatory policies (20% of waste TV affected); 2.a) recycled content (20%) in voluntary policies; 2.b) recycled content (40%) in voluntary policies.

market would be designed in the future to be in line with the requirement. Benefits in terms of additional recycled materials in the EU would amount from $1 \cdot 10^6$ [kg] to $2 \cdot 10^6$ [kg] of HI-PS respectively, corresponding to around 0.1% of polystyrene used in the EU-27 in 2010. The related lifecycle savings for the "Abiotic Depletion – fossil" impact category have been calculated (Table 10).

Table 10 also illustrates the lifecycle benefits related to each measure normalized to the estimated impacts of the LCD-TV product group.

Finally, it was not possible to quantify the potential environmental benefits of Measure $n°3$ for the EU. However, according to recyclers, the provision of additional information on the LCD screen composition will contribute to the development of recycling plants for indium in Europe. It is highlighted that currently more than seventy per cent of all the indium consumed in the EU-27 is utilized in flat display panels and all the indium is imported from extra-EU countries (EC, 2010c). The recycling of indium from waste LCD-TV could therefore decrease the dependency from imports.

5. Applications of the method: advantages and limits

The REAPro method allows to assess the resource efficiency of a selected product considering a set of different criteria. In particular, the method is structured in order to drive the practitioners through the analysis of EoL treatments and to identify potential areas of improvement.

The method is an answer to the need of robust tools for the assessment of resource efficiency of products, as identified by some researchers and by stakeholders of policies. The outcomes of the method can serve the policy debate on possible strategies for the improvement of EoL performances of EuP. In particular the systematic analysis of the EoL scenarios and the use of quantified environmental based indices represent an innovative contribution to the development of product policies.

As illustrated in the case-study analysis, the REAPro method can be used to cross-compare different potential product measures related to one considered EuP group. Benefits of potential measures could be also compared among different product groups and different policies.

The REAPro method is proving to be applicable and relevant to current EU policies; some of the presented results are being used as input for some on-going policy processes (e.g. the revision of Ecodesign measure for televisions (EC, 2012)), and it is currently under discussion the potential integration of the presented Recyclability index into the European methodologies for the environmental assessment of products (BIOis, 2013).

The method is also applicable by manufacturers for self-assessment of products, continuous improvement (through the implementation of ecodesign strategies) and declaration/labelling of product performances.

The REAPro integrates a set of relevant environmental criteria, as identified in the literature review. However, to cover even more comprehensively the area of resource efficiency of products, other additional criteria could be introduced, as for example the durability, the dematerialisation and the use of renewable resources. These can be part of further developments of the method. It is further noticed that the proposed method is specifically developed to identify and assess potential product's measures from the environmental point of view. However, the feasibility and enforceability of such measures is subjected to the check of their viability under other aspects (e.g. economic factors, compliance to safety regulations). This check is, for example, a standard practise in the European policies where a comprehensive impact assessment is developed for each proposed measures (EC, 2009). Therefore the outcomes of the method have to be considered as potential inputs for more comprehensive decisional processes, analysing different possible alternatives under various aspects of sustainability.

Some difficulties in the application of the method could relate to the data availability. The calculation of the indices, in fact, need a detailed BoM, the definition of EoL scenarios (representative for the considered geographical and temporal context), and the availability of various life cycle information for the considered product. Concerning this last, the current analysis identified a general lack in the commonly available life cycle databases of inventory data about recycled materials (especially plastics) and their loss of quality after recycling (downcycling). Some additional uncertainties in the assessment could also rise for innovative products or products affected by quick technological changes due to the consequent changes in recycling plants.

Recyclability/recoverability rates are also other key inputs of the method. Currently, the IEC (2012) represents the most robust data source. However, it is highlighted the need of representative, detailed and continuously update information on EoL treatments and related recovery yields.

6. Conclusions

The article presents a method, named REAPro (Resource Efficiency Assessment of Products), for the assessment of resource efficiency of products according to several criteria. In particular, the following criteria have been selected as relevant for EuP: Reusability/Recyclability/Recoverability (in mass and in terms of environmental impacts); Recycled content (in mass and in terms of environmental impacts); Use of hazardous substances.

The REAPro method is based on five subsequent steps, initially addressed to the identification of product's hot spots (i.e. product's parts that are relevant for some resource efficiency criteria for the considered EoL treatments). Successively the method identifies potential product's measures for the improvement of the resource efficiency and assesses these measures at the case-study level and at the product group level. Product's measures can be suitable for different policies, including requirements for mandatory policies (e.g. enforced via the EU Ecodesign Directive), and voluntary policies (e.g. environmental labelling schemes or environmental claims).

The five steps of the method have been applied to an exemplary EuP case-study: a 20″ LCD-TV. The analysis of the case study has been based on information provided by some representative European recycling plants. In particular, the case-study analysis identified some product's parts that are relevant for one or more considered criteria: Printed Circuit Boards – PCB (for the environmentally based recyclability and for the use of hazardous substances); large plastics parts, mainly HI-PS frames (for the recyclability and recycled content criteria) and PMMA board (for the recyclability in mass); compact fluorescent lamps – CFL (for the content of mercury).

Three exemplary measures have then been identified and assessed:

- the minimum dismantling time of some key parts (PCB, LCD screen, PMMA and CCFL), in order to improve the recyclability of the product and to grant additional masses of recycled material and related environmental benefits.
- Introduction of a 20% threshold of post-consumer recycled content in large plastic parts, to boost the demand in the market for materials with low values when recycled, otherwise landfilled or energy recovered.
- The provision of additional information concerning the content of indium in the LCD screens (currently landfilled) to promote the development of technologies for their recycling.

However, these measures are not equally suitable for all product policies. The same measure can be adapted to different purposes. In particular, the measure on dismantlability is potentially suitable for mandatory requirements once standardized methods for the measurements of the dismantling time would be developed. This measure can produce a large reduction of various lifecycle impacts of the product, including: the “Abiotic Depletion – element” (reduction of about 70%), “Aquatic Ecotoxicity” (28%), “Human toxicity” and “Terrestric Ecotoxicity” (20%).

The measure on the minimum content of recycled materials could be applied first via voluntary policies, mainly due to observed difficulties for the verification of the compliance to the requirement. For the considered case study LCD-TV, this measure could contribute to increase the recycling of post-consumers plastics (about 300 g) and to reduce the lifecycle “Abiotic Depletion – fossil” of about 0.4%. Mandatory policies could introduce less restrictive measures related to the recycled content based, for example, on the declaration of the recycled content of some key parts.

The declaration of the content of indium could be enforced by both voluntary and mandatory policies. Benefits potentially achievable have been assessed qualitatively due to a lack of information about the impacts of the processes for the recycling of indium.

The presented case-study analysis also proves to be relevant to current EU policies and some of the results are being used as input for some on-going policy processes.

Disclaimer

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