Mass balance and life cycle assessment of the waste electrical and electronic equipment management system implemented in Lombardia Region (Italy)

L. Biganzoli *, A. Falbo, F. Forte, M. Grosso, L. Rigamonti

Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza L. da Vinci 32, 20133 Milano, Italy

Received 18 December 2014
Received in revised form 31 March
2015 Accepted 12 April 2015

Abbreviations: ABS, acrylonitrile butadiene styrene; CED, Cumulative Energy Demand; CFC, chlorofluorocarbon; CH, Swiss context; CRTs, cathode ray tubes; DE, German context; EI, ecoinvent; FPDs, flat panel displays; FU, functional unit; GLO, global context; IT, Italian context; LCA, life cycle assessment; LCD, liquid crystal display; LCIA, life cycle impact assessment; LHV, lower heating value; MFA, material flow analysis; MMA, methyl methacrylate; NiMH, Nickel Metal Hydride; O.R.SO., Osservatorio Rifiuti Sovraregionale (regional waste observatory); PEF, product environmental footprint; PET, polyethylene terephthalate; PMMA, poly(methyl methacrylate); PS, polystyrene; PWBs, printed wiring boards; R1, heaters and refrigerators; R2, large household appliances; R3, TV and monitors; R4, small household appliances; R5, lighting equipment; RER, European context; UCTE, Union for the Co-ordination of Transmission of Electricity; UM, unit of measure; WEEE, waste electrical and electronic equipment.

* Corresponding author.

E-mail address: laura.biganzoli@mail.polimi.it (L. Biganzoli).

1. Introduction

Waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams in Europe, with a growth rate of approximately 3–5% per year (European Commission, 2014). Due to the presence of hazardous substances, such as heavy metals (for example, mercury and lead in fluorescent lamps and batteries) and flame retardants, if improperly managed it might pose significant human health and environmental risks (Tsydenova and Bengtsson, 2011). On the other hand, it must be regarded as an important source of valuable materials, because of the presence of plastics, glass, base and precious metals, and rare earth ele-ments that can be recovered (Cui and Zhang, 2008; Tuncuk et al., 2012). For example, precious metals such as gold and palladium occur in concentration more than tenfold higher in printed wiring boards (PWBs) than in commercial mined minerals (Betts, 2008).

For all the above mentioned reasons, the interest in the WEEE treatment and recovery has largely increased in recent years, and several papers have been published regarding specific WEEE streams and their treatment options. For example, Li et al. (2007) investigated the possibility to recover the PWB by means of mechanical treatments including a shredding stage and the separation of the metallic fraction through a corona electrostatic separation process. Mechanical processes are widely used for WEEE disassembly and for the separation of the metallic fractions. An extended analysis of the mechanical processes available for WEEE treatment was carried out by Cui and Forssberg (2003), showing that in order to achieve the maximum recovery of the materials, WEEE should be shredded to small particles, generally below 5 mm or 10 mm. Material recovery from WEEE is not restricted to the sole metallic fraction. Plastic and glass can be also recovered. For example, Andreola et al. (2007) investigated the possibility to reuse the glass separated from cathode ray tube (CRT) TV and monitors in the ceramic glaze industry and estimated the environmental performance of this practice.

Life cycle assessment (LCA) is a fundamental tool to assess the envi-ronmental benefits and burdens associated with waste management. However, up to now, LCA studies involving WEEE have typically been applied on a single product, eventually including focuses on different management alternatives (Andrea and Andersen, 2010; Johansson and Bjorklund, 2009; Lu et al., 2006; Park et al., 2006). Comprehensive stud-ies assessing the environmental benefits and burdens of the overall WEEE collection and recovery system at a regional or national level are hardly available. Hischier et al. (2005) examined the two WEEE take-back and recycling systems implemented in Switzerland and defined their environmental impacts by means of a combined approach of material flow analysis (MFA) and LCA. The study was then updated by Wäger et al. (2011), by introducing new treatment options and improving the dataset used for the modelling of the treatment of the various WEEE fractions.

In Italy, WEEE is classified in five categories (DM n. 185 of the 25th of September, 2007): heaters and refrigerators (R1), large household ap-pliances (R2), TV and monitors (R3), small household appliances (R4) and lighting equipment (R5). Their separate collection started in 2005, when the European legislation (Directives 2002/95/CE, 2002/96/CE and 2003/108/CE) was implemented by means of the national Decree 151/2005. In 2011, an average of 4.7 kg of WEEE per capita was collected in Lombardia Region (Centro di Coordinamento RAEE, 2011).

This study is a part of a wider research project involving Regione Lombardia. The first part focused on municipal solid waste, whose management system was analysed by means of LCA in order to assess the current situation and to give useful strategic indications for future waste management (Rigamonti et al., 2013a, 2013b). The second part, which is described in the current paper, focused on the WEEE stream.

The research investigates the WEEE management system in Lombardia Region in the year 2011 by applying the LCA methodology. Contrary to previous studies (Hischier et al., 2005;Wager et al., 2011), the analysis was carried out on each of the five WEEE categories, as well as on the overall WEEE management system. An extensive collection of primary data was carried out to assess the mass balance of the treatment plants; the benefits and burdens associated with the treatment and recovery of each category were then evaluated. Results obtained separately for the five categories were finally used to assess the environmental performance of the overall WEEE management system implemented in the Region and to identify potential for improvements.

The level of detail of the assessment allows extrapolating the findings to other European regions, at least for a first screening of the WEEE management system.

2. Materials and methods

The study was carried out to quantify the mass balance of the WEEE management system in Lombardia Region in the year 2011 and to assess its environmental benefits and burdens following an LCA approach. The five WEEE categories were analysed separately, and then the results were merged in order to get the complete picture of the WEEE manage-ment scheme. Overall 46.070 tonnes were collected in 2011 in Lombardia Region, split as follows: 21.4% of R1, 21.1% of R2, 36.5% of R3, 20.4% of R4 and 0.6% of R5 (Centro di Coordinamento RAEE, 2011).

The LCA methodology was applied in all its four basic stages (ISO, 2006): goal and scope definition, inventory analysis, impact assessment and interpretation. The assessment was carried out with the support of the SimaPro (version 7.3.3) software. For each unit, a new module was designed, including the energy and material consumption, the direct emissions as well as the substituted materials and energy, with the same approach adopted in previous studies (Rigamonti et al., 2010, 2013a, 2013b).

2.1. Goal and scope definition

Three are the goals of the study:

1) the evaluation of the mass balance of the treatment and recovery system of the five WEEE categories defined by the Italian legislation;
2) the assessment of the environmental performance of the treatment and recovery system of each WEEE category, with the aim to understand if the benefits arising from the material and energy recovery are offsetting the burdens due to the processing of the waste itself;
3) the evaluation of the environmental performance of the overall WEEE management system implemented in Lombardia Region in the year 2011.

The results of the study were used to support the regional authorities in the identification of the critical aspects of the current WEEE management system and of its possible improvement.

The functional unit (FU) was defined as 1 tonne of collected WEEE for each of the five categories. Waste composition is not known in terms of type of equipment (e.g., for R4 the presence of each type of appliances in 1 tonne), but it could be assessed on the basis of the outputs of the first treatment plants, in terms of recovered components (e.g., batteries and motors) and materials (e.g., plastics, aluminium and ferrous metals). In fact for a very heterogeneous waste stream such as WEEE (and the R4 category in particular), a characterisation based on the outputs of the first treatment plants turned out to be more representative and more relevant from a recovery perspective, than the traditional analysis of the waste input composition.

The system boundaries include all the treatment processes, from the moment the waste is collected to when it leaves the system as an emis-sion (solid, liquid or gaseous) or as a secondary raw material, following the “zero burden assumption” (Ekvall et al., 2007). They thus included the collection of the waste, its transport to the collection platform, the pre-processing (here referred to as “first treatment plant”) and the sub-sequent treatment of the separated components in the final recycling/disposal plants, as shown in Fig. 1.

The geographical scope of the study was regional and the study focused on conditions and technologies for 2011 (i.e., the WEEE

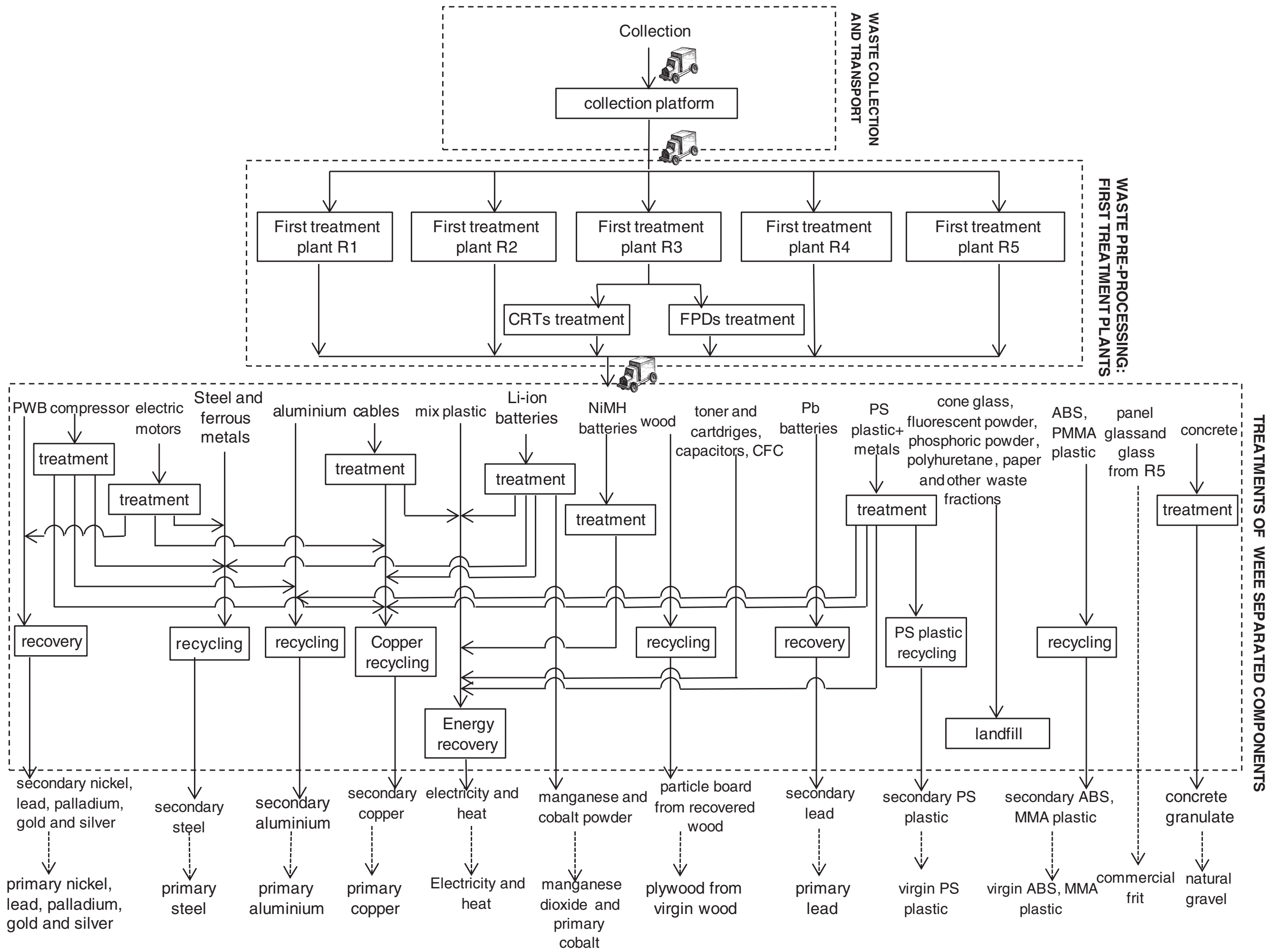

Fig. 1. System boundaries of the WEEE management system. WEEE is collected and delivered to the first treatment plants, where it is disassembled among its major components. The components are then shipped to dedicated recycling/disposal plants. Recovered secondary materials and energy substitute for the corresponding primary products.

management system in Lombardia Region as it was implemented in 2011).

Cases of multifunctionality were resolved by expanding the system boundaries to include avoided primary productions due to material and energy recovery from waste (EC JRC-IES, 2010; Finnveden et al., 2009). Avoided material and energy productions were based on average technologies. More details are given in Section 2.2 “Life cycle inventory”.

Primary data were used in the modelling of the foreground system, in particular for the mileage for waste collection and transport, the mass and energy balances of the first treatment plants and of the treatment of some of the separated components. These data derived from the regional database O.R.SO. (*Osservatorio Rifiuti Sovraregionale*) and from field visits to the main treatment plants located in Lombardia Region. For some components primary data were not available and so data from literature and from the ecoinvent (EI) database version 2.2 (Swiss Centre for Life Cycle Inventories, 2010) were used. This was the case, for example, of PWBs, polymethyl methacrylate (PMMA) plastic, Li-ion and Nickel Metal Hydride (NiMH) batteries. The same is valid for the modelling of the background processes (e.g., avoided produc-tions). More details are reported in Section 2.2.

Capital goods were included in the analysis just for the background processes

13 impact categories with the related characterisation methods recommended by the Product Environmental Footprint (PEF) guide (EC, 2013) were selected: Climate change, Ozone depletion, Human toxicity-cancer effects, Human toxicity-noncancer effects, Particulate matter, Photochemical ozone formation, Acidification, Terrestrial eutrophication, Freshwater eutrophication, Marine eutrophication, Freshwater ecotoxicity, Water resource depletion and Mineral and fossil resource depletion. However, for the category Mineral and fossil resource depletion, the PEF characterisation factors, calculated as a function of the “reserve base” of each resource, were substituted with those calculated by Van Oers et al. (2012), based on the “ultimate reserve” of these resources.[1] Among the categories for which a characterization method is recommended by the PEF guide, only those regarding the effects on the human health of ionising radiations and land use were excluded. No specific inventory data covering these issues were indeed collected when new unit processes had to be modelled. In addition to the PEF impact categories, the Cumulative Energy Demand method was chosen to evaluate the energy consumption of the system (Hischier et al., 2010). Long-term emissions are included in the analysis.

[1] Factors based on “ultimate reserves” are indeed those used in the baseline version of the recommended characterization method (the so-called CML method, Guinée et al.(2002)) and their use was deemed more appropriate since no uncertainties associated with considerations on technical and economic availability of resources are introduced in their estimate.

2.2. Life cycle inventory

This section reports in details all the data and assumptions for the modelling of the collection and transport of the waste, of its treatment in the first treatment plants, of the transport of the separated components and of their treatment in dedicated recycling/disposal plants, as well as of the avoided materials and energy.

2.2.1. WEEE collection

WEEE collection was modelled considering that the waste can be both collected on-demand by the public service or delivered by the citizens to the collection platform, as reported in Table 1. An average mileage of 20 km/FU was assumed for the on-demand collection system, whereas 4.2 km/FU was assumed for the direct delivery of the waste to the collection platform. To calculate the impact, for both collec-tion systems, it was assumed that the waste is collected with small vans, described by using the EI dataset *Transport, van <3.5 t/RER*.

2.2.2. WEEE transport from the collection platforms to the first treatment plants

WEEE transport from the collection platforms to the first treatment plants was modelled by processing the data reported in the regional database O.R.SO. and considering the geographical localisation of the most important plants. The resulting average distance between the collection platforms and the first treatment plants is reported in Table 2. The EI datasets *Transport, lorry 3.5–7.5 t/EURO 3* and *Transport, lorry 3.5–7.5 t/EURO 4* (50% each) were used for the modelling of the transport.

2.2.3. First treatment plants

Current WEEE management in Lombardia Region was identified by firstly determining the streams from the collection platforms to the so-called "first treatment plants". Such term indicates those facilities where WEEE is dismantled in order to safely remove the hazardous components and to separate the valuable materials that will be delivered to the recycling or disposal processes. The most important treatment plants were identified by applying a 15% cut-off to the total treatment capacity at the provincial level. Then, the WEEE stream assessment at the regional level was obtained by summing up the contribution of the twelve provinces. Primary data were thus gathered dur-ing field visits at some selected treatment plants and they were used to model the mass balance and the energy consumption for each WEEE category.

A detailed description of the first treatment plants is reported in the Additional materials (Chapter A), whereas the amount of components separated from WEEE treatment is summarised in Table 3. The R3 category includes both cathode ray tube (CRT) TV and monitors and flat-panel displays (FPDs) (97.6% and 2.4% of the overall R3 category, re-spectively, on the basis of the data collected during the field visits of the treatment plants in Lombardia Region). The modelling of CRT TV and monitors and FPDs was carried out separately, due to the differences in the waste composition and in the recovery process.

Electricity consumption, reported in Table 3, was modelled by the EI dataset *Electricity, medium voltage, at grid/IT*.

Table 1
Percentage of WEEE collected on-demand and delivered to the collection platform. Source: processing of data reported in O.R.SO. database.

WEEE category	On-demand collection	Collection platform
Heaters and refrigerators (R1)	17.8%	82.2%
Large household appliances (R2)	15.4%	84.6%
TV and monitors (R3)	17.6%	82.4%
Small household appliances (R4)	15.4%	84.6%
Lighting equipment (R5)	3.5%	96.5%

Table 2
Average distances from the collection platform to the first treatment plants.

WEEE category	Distance (km)
Heaters and refrigerators (R1)	96.0
Large household appliances (R2)	79.4
TV and monitors (R3)	51.6
Small household appliances (R4)	58.7
Lighting equipment (R5)	79.4

2.2.4. Transport of the separated components

The transport of the separated components from the first treatment plants to dedicated disposal or recovery plants was modelled according to primary information given by the plant operators, otherwise assump-tion was made by the authors. Data used in the study are summarised in Table 4. For the modelling, the EI dataset *Transport, lorry <16 t, fleet average/RER* was used.

2.2.5. Treatment of the separated components

Components separated in the first treatment plants are sent to dedicated disposal or recovery plants. A brief description of the modelled treatments, with the corresponding recovered material and energy, is reported in Table 5. Note that the treatment of some components (e.g., compressor and fluorescent plants) implies their separation into smaller components, which are then sent to further treatments. All these treatments were modelled according to primary data when available, otherwise data from literature and from EI database were used. More details are reported in the Additional materials (Table B).

2.2.6. Avoided products

Avoided materials displaced by secondary products are reported in Table 6. The amount of avoided materials were calculated by adopting a 1:1 substitution ratio when the quality of the secondary material can be assumed the same of the virgin one, as for metals and glass, and a ratio below one when the quality is lower. The latter is the case of wood, for which a 1:0.6 substitution ratio was adopted (Rigamonti et al., 2010), and of ABS (acrylonitrile butadiene styrene) and PS (polystyrene) plastics, for which the same 1:0.81 substitution ratio used for PET (polyethylene terephthalate) by Rigamonti et al. (2009) was applied. ABS and PS plastics are in fact recycled through a mechanical process (like PET) but no specific information about their recycling process and the quality of the secondary material were available. Instead, for the PMMA plastic a 1:1 substitution ratio was adopted, since its chemical recycling allows obtaining a high purity monomer which can be used in substitution of an equal amount of virgin MMA (Kikuchi et al., 2014). For plasmix, 1 kg was assumed to substitute 0.62 kg of petcoke in co-combustion, based on the ratio between the respective lower heating value (LHV), equal to 20.100 $kJ \cdot kg^{-1}$ and 32.475 $kJ \cdot kg^{-1}$, respectively (Rigamonti et al., 2013a). The modelling of the avoided materials production was based on the European or global average technologies, according to the availability in the EI database, as reported in detail in the Additional materials (Table C).

Avoided electricity was modelled as produced by the Italian or European electricity mix (EI datasets *Electricity, medium voltage, at grid/IT* and *Electricity, medium voltage, production UTCE/at grid*), depending on the location of the treatment plant (i.e., Italy or Europe). Avoided thermal energy was modelled as heat produced by domestic gas-fired boilers for the Italian context (Grosso et al., 2012) and by a mix of 50% domestic gas-fired and 50% domestic coal-fired boilers for the European one (EI datasets *Heat, natural gas, at boiler atmospheric non modulating <100 kW/RER* and *Heat, hard-coke, at stove 5–15 kW/RER*).

Table 3
Components separated from WEEE and electricity consumption of the first treatment plants. Values are reported as percentage of the plant input (assumed equal to 100%).

Separated components	Heaters and refrigerators (R1)	Large household appliances (R2)	TV and monitors (R3)		Small household appliances (R4)	Lighting equipment (R5)
			CRTs	FPDs		
ABS plastic	–	–	14.9%	20.7%	–	–
Aluminium	5.0%	0.4%	0.5%	10.2%	1.4%	4.0%
Brass	–	–	–	–	0.2%	–
Cables	0.4%	0.6%	1.3%	1.4%	2.8%	–
Capacitors	–	0.2%	0.1%	0.3%	0.2%	–
CFC 11–CFC 12	0.4%	–	–	–	–	–
Chromium steel	–	2.8%	–	–	–	–
Compressor	13.2%	–	–	–	–	–
Compressor oil	0.3%	–	–	–	–	–
Concrete	–	9.6%	–	–	–	–
Cone glass	–	–	16.5%	–	–	–
Deflection coins	–	–	3.1%	–	–	–
Electron guns	–	–	0.2%	–	–	–
Fluorescent lamps	–	–	–	0.4%	–	–
Fluorescent powder	–	–	5.4%	–	–	–
Glass to recycling[a]	–	–	35.5%	3.4%	–	80.0%
Hard disk	–	–	–	–	0.6%	–
LCD panel[b]	–	–	–	7.9%	–	–
Li and NiMH batteries	–	–	–	–	0.1%	–
Mix of plastic to energy recovery	–	–	–	–	31.3%	–
Motors	–	4.5%	–	–	7.1%	–
Other waste to landfill	2.1%	0.3%	0.2%	4.4%	1.0%	1.5%
Paper and cardboard	–	–	–	–	–	1.5%
Pb batteries	–	–	–	–	0.2%	–
Phosphoric powder	–	–	–	–	–	8.0%
PMMA plastic	–	–	–	4.7%	–	–
Polyurethane	17.5%	–	–	–	–	–
Power supplies	–	–	–	–	1.8%	–
PWBs	–	–	9.3%	8.3%	3.0%	–
Stream "PS plastic + metals"[c]	17.6%	9.5%	–	–	–	–
Steel and ferrous metals	41.5%	72%	11.0%	38.4%	50.1%	5.0%
Toners and Cartridges	–	–	–	–	0.2%	–
Transformers	–	–	0.3%	–	–	–
Wood	1.8%	0.1%	1.7%	–	0.1%	–
Electricity consumption (kWh/t)	100	66	30	26.5	66	96

[a] Panel glass from CRTs, glass sheet from FPDs and glass from lighting equipment.
[b] LCD panels are stocked at the plant, because no commercial recycling process is available yet.
[c] 68% PS plastic + 29% plastic impurities (plasmix) + 3% metals (1% copper and 2% aluminium).

2.3. Sensitivity analysis

A sensitivity analysis is used to assess the influence of possible changes in the input parameters on the final results (ISO/TR, 14049, 2000). In this study, a sensitivity analysis was performed to understand how the results are influenced by the assumptions about the composi-tion of the R3 category (in terms of percentage of FPDs) and about the metals substitution ratio.

2.3.1. Percentage of FPDs in the R3 category

In the study, a percentage equal to 2.4% of FPDs in of the overall R3 category was assumed, on the basis of the data collected during the field visits of the treatment plants in Lombardia Region. However, considering the recent market trends, the percentage of FPDs in the R3 category is due to increase in the future (Habuer et al., 2014). In fact, CRT technology has been extensively substituted by liquid crystal displays (LCDs), and in the last years new display models based on the led technology have been commercialised. In the sensitivity analysis, a mass weight of FPDs ranging from 5% to 50% was assumed (5/10/15/50%).

2.3.2. Metal substitution ratio

LCA studies often consider a 1:1 substitution ratio of recycled to virgin metals (Johansson and Bjorklund, 2009). Moreover, despite the key role that the choice of the substitution ratio can play on LCA results was demonstrated by different authors (Bovea et al., 2010; Rigamonti et al., 2009), only few papers have investigated this aspect for the specific case of metals (Allegrini et al., 2015). However, it is well known that during the recycling process a percentage of impurities and unwanted alloying elements can remain in the metallic phase, thus reducing the quality of the secondary metal (Bartl, 2014). Steel and aluminium are then actually susceptible to downcycling because of the accumulation of alloying elements in the secondary metals, which cannot be separated during the melting process. Accumulated alloying elements become tramp elements, thus they limit the application of the material or require the addition of high-quality scrap, or even of pure primary metals (Allegrini et al., 2015). Downcycling does not affect copper and precious metals since, despite alloying and unwanted metals can be present after melting, the application of electrorefining processes effectively removes other metals present in the scraps. Secondary copper, gold, silver and palladium have thus the same quality of the corresponding primary materials. A 1:0.9 substitution ratio was then calculated for aluminium, based on the ratio between the market price of secondary alloys and primary aluminium at the London Metal Exchange (Koffler and Florin, 2013). The same value was assumed also for the ferrous metals and chromium steel, in the lack of more specific indications.

3. Results and discussion

3.1. Overall mass balance

Based on the inventory previously described, the overall mass balance of the treatment and recovery system of each WEEE category was

Table 4
Transport of the separated components to specific treatment/disposal plants.[a]

Separated component	Destination	km	Note
Steel and ferrous metals	Plants located in Lombardia Region	50	[(1)]Average situation between the case in which the WEEE treatment plant has a line dedicated to the R5 category (and thus the transport is not present) and the case in which lamps are transported in plants located outside Lombardia Region
Aluminium			
ABS plastic			
Stream "PS plastic + metals"			
Mix of plastic			
Wood			
Fluorescent lamps			
Other waste			
Cone glass			
Toners and cartridges			
Fluorescent powder			
Concrete			
Phosphoric powder containing mercury			
Paper and cardboard			
Pb batteries	Plants located in Italy	100	Average distance
CFC	Plants located in Italy	100	Authors assumption (The exact destination is not known)
Compressor oil			
Polyurethane			
Cables			
Motors			
Hard disk			
Deflection coils			
Electron guns			
Transformers			
Compressor			
Power suppliers			
Li-ion and NiMH batteries	Plants located in France or Switzerland	500	Average distance
Panel glass	Plant located in Emilia Romagna Region (Italy)	250	
Glass sheet			
Glass from lighting equipment			
Capacitors	Plant located in Ravenna (Italy)	300	
PWBs	Plants located in Germany, Belgium and Switzerland	1000	Average distance
PMMA plastic			

[a] Brass is not included due to a lack of information.

calculated. Secondary materials and energy recovered from 1 tonne of each WEEE category are reported in Table D of the Additional materials. By adopting the substitution ratios listed in Table 6, the amount of avoided primary materials and energy arising from 1 tonne of R1, R2, CRTs, FPDs, R4 and R5 was evaluated and is shown in Table 7. Savings are dominated by steel and commercial frit, the first coming mainly from the recovery of the R1, R2 and R4 categories and of the FPDs, the latter from the recovery of the CRTs and of the R5 category. The production of a non-negligible amount of virgin ABS and PS plastics is also avoided, thanks to WEEE recovery. Small amounts of precious metals, such as gold, silver and palladium are saved, which will likely result in relevant environmental savings due to the high impact of their primary production.

Finally, electric and thermal energy savings are obtained mainly thanks to the recovery of the R4 category.

3.2. Life cycle impact assessment (LCIA) results and interpretation: analysis of the five WEEE categories

Based on the overall mass balance, the potential environmental impacts associated with the treatment of 1 tonne of each WEEE category were evaluated. The results are listed in Table 8, which reports separately the contribution of the waste collection and transport to the first treatment plant and that of the actual treatment process, including the recovery of the separated components and the benefits associated with the avoided products. For the R3 category, the contribution of the treatment plant is reported separately for CRTs and FPDs, considering that they represent 97.6% and 2.4% of the overall R3 waste, respectively. According to the common practice in LCA studies, positive values mean a burden for the environment, while negative ones mean savings.

Overall, the benefits arising from the material and energy recovery of WEEE offset the burdens due to the processing of the waste itself, with the following exceptions:

- R1 category: ozone depletion, human toxicity (both cancer and non-cancer effects), marine eutrophication and freshwater ecotoxicity;
- R2 category: ozone depletion, human toxicity (both cancer and non-cancer effects), freshwater ecotoxicity and water resource depletion;
- R4 category: human toxicity (cancer effects) and freshwater ecotoxicity;
- R5 category: human toxicity (cancer effects).

The recovery of TV and monitors (R3 category) is the one that gives the highest environmental advantages, with benefits in all the impact categories.

For all the WEEE categories, the burdens of the waste collection and transport to the treatment plants result negligible compared to the burdens/savings of the overall treatment process.

The contribution analysis of the WEEE treatment processes (excluding the collection and the transport of the waste to the first treatment plant) is reported in Fig. 2.

In general, the energy consumption of the first treatment plants (contribution "energy consumption" in Fig. 2) is not negligible, with the only exception of the R3 category. Detailed comments for each WEEE category follow in the subsequent paragraphs.

3.2.1. Heaters and refrigerators (R1)

For the R1 category, the main contributions to the impact indicators are the recovery of the metals (ferrous and aluminium scraps and metals in compressors) and of the stream "PS plastic + metals". The

Table 5
Treatment of the separated components and corresponding recovered material and energy.

Separated component	Treatment process	Recovered material/energy
ABS plastic	Material recycling	Secondary ABS
Aluminium	Material recycling in smelter	Secondary aluminium ingots
Brass[a]	Not included	Not included
Cables	Shredding and separation of materials	Copper to material recycling and plastic to energy recovery
Capacitors	Disposal to hazardous waste incineration	Electricity and heat
CFC11–CFC 12	Disposal to hazardous waste incineration	–
Chromium steel	Material recycling in smelter	Liquid secondary steel
Compressor	Shredding and separation of materials	Steel, aluminium and copper to material recycling in smelter
Compressor oil[a]	Not included	Not included
Concrete	Shredding and material recovery	Natural gravel
Cone glass	Disposal to hazardous waste landfill	–
Fluorescent lamps	Dry dismantling process	Steel and aluminium to material recycling in smelter; glass to recovery in ceramic industry; phosphoric powder containing mercury to hazardous waste landfill
Fluorescent powder	Disposal to hazardous material landfill	–
Mix of plastic	Energy recovery	Electricity and heat
Motors	Shredding and separation of materials	Plastic to energy recovery; aluminium, iron and copper to material recycling in smelter; PWBs with precious metals to specific processes
Other batteries and accumulators (45% Li-ion and 55% NiMH batteries)	Li-ion batteries to mechanical process	Plastic to energy recovery; steel and non-ferrous metals to material recycling in smelter; MnO_2 to recycler and Co powder to cobalt industry
	NiMH batteries to pyrometallurgical process	Plastic to energy recovery Recovery of Ni–Co–Fe residues was not included in the study
Other waste	Disposal to inert waste landfill	–
Panel glass, glass sheet and glass from lighting equipment	Recovery in the ceramic industry	–
Paper and cardboard	Disposal to sanitary landfill	–
Pb batteries	Shredding and remelting of the lead acid in shaft furnace	Secondary lead
Phosphoric powder containing mercury	Disposal to hazardous waste landfill	–
PMMA plastic	Material recycling (chemical process)	Secondary MMA
Polyurethane	Disposal to sanitary landfill	–
Power supplies, hard disk, electron guns, deflection coils, transformers[b]	Shredding and separation of materials	Not included
PWBs	Material recycling in smelter and further refinery	Secondary copper; secondary nickel; secondary lead; secondary precious metals (gold, silver, palladium)
Stream "PS plastic + metals"	Material selection	PS plastic to material recycling; plasmix to co-combustion in cement kiln; aluminium and copper to material recycling in smelter
Steel and ferrous metals	Material recycling in smelter	Liquid secondary steel
Toners and cartridges	Disposal to municipal waste incineration	Electricity and heat
Wood	Material recycling	Particle board

[a] Neither the treatment process nor the recovered materials were included in the model due to a lack of information.
[b] Only the treatment process was modelled, whereas the recovered materials were not included in the model due to a lack of information.

recovery of such a stream gives important benefits, mainly to the impact indicators water resource depletion, mineral and fossil resource depletion and the CED, thanks to the recovery of PS plastic, aluminium, copper and plasmix.

Ferrous scrap recovery gives a benefit or a burden depending on the impact category. For example, it gives a burden to the human toxicity (both cancer and non-cancer effects), freshwater ecotoxicity, ozone depletion and water resource depletion indicators. For the human toxicity (cancer effects) and the freshwater ecotoxicity indicators, the burdens are related to the disposal of the furnace slag produced by the ferrous scrap recycling process, as a consequence of the direct emission of chromium in the water compartment. For the impact indicators ozone depletion, human toxicity (non-cancer effects), and water resource depletion, the burdens are mainly associated with the direct gaseous emission of bromotrifluoromethane, zinc and mercury and to the energy consumptions of the recycling process, as well as to the furnace slag disposal for the human toxicity (non-cancer effects) indicator.

A similar behaviour is observed for aluminium recovery. Despite being beneficial for most of the impact categories, it implies burdens in the impact category human toxicity (non-cancer effects). This is mainly related to the production of zinc, which is used as alloying element in the melting process for secondary aluminium production.

The burden in the impact category ozone depletion is mainly due to the presence of CFCs in the waste, and thus to their direct emission into the atmosphere when they are incinerated.

Polyurethane landfilling gives a burden to the marine eutrophication impact indicator, as a consequence of the direct emissions of nitrogen compounds in the water compartment.

3.2.2. Large household appliances (R2)

The main benefits of the treatment and recovery of the large household appliances (category R2) derive from metals (ferrous scraps and metals in cables, motors and in the stream "PS plastics + metals") and plastic recovery (from stream "PS plastics + metals").

As for the R1 WEEE category, ferrous scrap recovery plays a double role. Despite being beneficial for most of the impact categories, it implies burdens in the toxic impact indicators (human toxicity and freshwater ecotoxicity) and in the ozone depletion and water resource depletion indicators.

Table 6
Secondary products obtained from WEEE treatment and corresponding avoided primary products assumed in the LCA. Substitution ratio is also reported.

Secondary product	Avoided primary product	Substitution ratio
Liquid secondary steel from iron scraps	Liquid primary steel from pig iron	1:1
Liquid secondary steel from chromium steel scraps	Liquid primary chromium steel	1:1
Secondary aluminium ingots from aluminium scraps	Primary aluminium ingots from bauxite	1:1
Secondary copper	Cathodes of primary copper	1:1
Secondary palladium	Primary palladium	1:1
Secondary silver	Primary silver from combined mining and refining of gold and silver	1:1
Secondary nickel	Primary nickel	1:1
Secondary gold	Primary gold from combined mining and refining of gold and silver	1:1
Secondary lead	Primary lead	1:1
Particle board from recovered wood	Plywood from virgin wood	1:0.6
Granules of recycled ABS	Granules of virgin ABS	1:0.81
Granules of recycled PS	Granules of virgin PS	1:0.81
Concrete granulate	Gravel for road construction	1:1
Manganese powder	Manganese dioxide from ore and ferromanganese	1:1
Cobalt powder	Primary cobalt	1:1
Recycled MMA monomer	Virgin MMA monomer	1:1
Plasmix	Petcoke in cement kiln	1:0.62
Glass granulate	Commercial frit for the ceramic glaze industry	1:1

For the impact indicator human toxicity (non-cancer effects), a significant burden is given by the recycling of the chromium steel. This is due to the gaseous emission of mercury from the melting furnace, as well as of zinc during the production process of the ferronickel used as an alloying element in the chromium steel production.

3.2.3. CRTs (R3)

The recovery of CRTs is beneficial for all the impact categories. The treatment and recovery of the PWBs are responsible for the majority of the overall savings, even if they represent less than 10% in mass of the CRT treatment outputs. The main benefits are associated with the recovery of the precious metals (gold, silver and palladium) as well as of copper (for more details about PWB recovery process see Chapter F of the Additional materials). For the impact categories climate change, ozone depletion, water resource depletion, mineral and fossil resource depletion and for the CED, important benefits come also from the recovery of the ABS plastic and of the panel glass.

3.2.4. FPDs (R3)

The treatment and recovery of FPDs are beneficial for all the impact indicators, with the exception of the human toxicity (cancer effects) as a consequence of the recovery of the ferrous metals. Ferrous metal recovery gives a burden also in the impact categories human toxicity (non-cancer effects), freshwater ecotoxicity, ozone depletion and water resource depletion.

Overall, the main benefits are related to the recovery of metals (ferrous and aluminium scraps and metals in PWBs) and to the recycling of PMMA and ABS plastics.

3.2.5. Small household appliances (R4)

For the R4 category, the main contributions to the impact indicators are associated with the recovery of metals (ferrous scraps and metals in PWBs, cables and motors). While the recovery of the PWBs is beneficial for all the impact indicators, thanks to the recovery of the precious metals and of copper, the recovery of ferrous scraps, cables and motors

Table 7
Avoided primary materials and energy associated with the treatment of 1 tonne of R1, R2, CRTs, FPDs, R4 and R5.

Avoided primary materials and energy	UM	Heaters and refrigerators (R1)	Large household appliances (R2)	TV and monitors (R3)		Small household appliances (R4)	Lighting equipment (R5)
				CRTs	FPDs		
ABS plastic	kg	–		91	127	–	–
Aluminium	kg	45.8	6.86	4	102	15.2	33.4
Chromium steel	kg	–	54.0[a]	–	–	–	–
Cobalt	kg	–	–	–	–	0.1	–
Commercial frit	kg	–	–	355	37.2	–	800
Copper	kg	11.5	8.56	28.9	27.2	29.1	–
Gold	kg	–	0.00011	0.02	0.02	0.005	–
Gravel	kg	–	96.0	–	–	–	–
Lead	kg	–	0.011	1.48	1.33	1.70	–
Manganese dioxide	kg	–	–	–	–	0.005	–
MMA plastic	kg	–	–	–	32.9	–	–
Nickel	kg	–	0.022	3.11	2.77	1.04	–
Palladium	kg	–	0.00022	0.03	0.03	0.01	–
Petcoke	kg	31.6	17.1	–	–	–	–
Plywood from virgin wood	m^3	0.0096	0.0005	0.009	–	0.0005	–
PS plastic	kg	73.2	39.5	–	–	–	–
Silver	kg	–	0.004	0.53	0.48	0.18	–
Steel	kg	471	665	97	384	490	44.1
Electricity	kWh	2.08	14.6	11.4	21.5	675	–
Thermal energy	MJ	4.67	15.9	16.4	20.2	1504	–

[a] 1 kg of secondary chromium steel is produced by 0.52 kg of chromium steel scraps, 0.26 kg of primary ferrochromium steel and 0.32 kg of primary ferronickel steel. Thus, 54 kg of secondary chromium steel are produced from 28.1 kg of chromium steel scraps recovered from 1 tonne of R2 and substitute 54 kg of virgin chromium steel.

Table 8
Impact indicators associated with the treatment and recovery of 1 tonne of R1, R2, R3, R4, and R5 in Lombardia Region (year 2011).

Impact category	UM	Heaters and refrigerators (R1)			Large household appliances (R2)			TV and monitors (R3)[a]				Small household appliances (R4)			Lighting equipment (R5)		
		Collection and transport	Treatment process	Total	Collection and transport	Treatment process	Total	Collection and transport	FPD treatment	CRT treatment	Total	Collection and transport	Treatment process	Total	Collection and transport	Treatment process	Total
Climate change	kg CO_2 eq.	58.96	−1,022	−963	50.36	−836	−786	38	−75	−2,149	−2,187	50	−788	−737	36.95	−863	−826
Ozone depletion	kg CFC-11 eq.	8.83E−06	8.12E−05	9.00E−05	7.53E−06	3.52E−05	4.27E−05	5.62E−06	−2.76E−06	−1.36E−04	−1.33E−04	7.53E−06	−5.39E−05	−4.64E−05	5.53E−06	−9.40E−05	−8.85E−05
Human toxicity (cancer effects)	CTUh	3.63E−06	1.68E−05	1.69E−03	3.09E−06	2.72E−03	2.72E−03	2.31E−06	1.51E−05	−1.074E−04	−8.70E−05	3.09E−06	1.70E−03	1.71E−03	2.27E−06	4.64E−05	4.86E−05
Human toxicity (non-cancer effects)	CTUh	4.99E−06	1.71E−04	1.76E−04	4.24E−06	1.91E−04	1.95E−04	3.12E−06	−3.17E−05	−1.86E−03	−1.89E−03	4.24E−06	−4.49E−04	−4.44E−04	3.12E−06	−4.71E−04	−4.68E−04
Particulate matter	kg PM2.5 eq.	0.03	−0.81	−0.78	0.02	−0.91	−0.89	0.02	−0.42	−18.37	−18.77	0.02	−6.94	−6.91	0.02	−0.77	−0.75
Photochemical ozone formation	kg NMVOC eq.	0.38	−4.68	−4.30	0.33	−3.41	−3.09	0.24	−0.95	−36.95	−37.66	0.33	−15.64	−15.32	0.24	−3.22	−2.98
Acidification	mol H^+ eq.	0.32	−5.89	−5.58	0.27	−6.63	−6.36	0.20	−8.24	−368.71	−376.76	0.27	−131.86	−131.59	0.20	−6.54	−6.34
Terrestrial eutrophication	mol N eq.	1.29	−10.17	−8.87	1.10	−9.33	−8.23	0.81	−1.63	−63.06	−63.88	1.10	−30.66	−29.56	0.81	−6.75	−5.94
Freshwater eutrophication	kg P eq.	0.01	−1.21	−1.20	0.01	−1.39	−1.38	0.01	−0.19	−7.78	−7.96	0.01	−4.01	−4.00	0.01	−0.44	−0.43
Marine eutrophication	kg N eq.	0.12	9.66	9.78	0.10	−0.85	−0.75	0.07	−0.15	−5.60	−5.68	0.10	−2.71	−2.61	0.07	−0.65	−0.58
Freshwater ecotoxicity	CTUe	57.21	16,198	16,255	49	26,323	26,371	36	−168	−15,278	−15,410	49	13,757	13,806	36	−258	−222
Water resource depletion	m^3 water eq.	0.08	−1.31	−1.23	0.07	0.73	0.80	0.05	−0.29	−11.16	−11.40	0.07	−3.75	−3.68	0.05	−4.31	−4.26
Mineral and fossil resource depletion	kg Sb eq.	0.17	−4.23	−4.06	0.14	−3.67	−3.53	0.11	−0.28	−8.89	−9.06	0.14	−5.59	−5.44	0.10	−3.43	−3.33
Cumulative Energy Demand (CED)	MJ eq.	1,010	−21,683	−20,673	863	−14,371	−13,508	649	−1,360	−39,103	−39,812	863	−24,102	−23,239	633	−20,506	−19,873

[a] Separated results for 1 tonne of CRTs and 1 tonne of FPDs are reported in the Additional materials (Table E).

gives a benefit or a burden depending on the impact category. For example, the recovery of ferrous metals implies a positive value of the human toxicity (cancer effects) and freshwater ecotoxicity indicators.

For the impact categories climate change, ozone depletion, water resource depletion, mineral and fossil resource depletion and the CED indicators, an important contribution to the impact indicators is also associated with the thermal recovery of plastic. This contribution results in a burden for the climate change category, as a consequence of the fossil carbon in the plastic, whereas it is beneficial for the other four categories, thanks to the displaced energy.

3.2.6. Lighting equipment (R5)

The treatment and recovery of the R5 category are beneficial for all the impact indicators, with the exception of the human toxicity (cancer effects), once again as a consequence of the recovery of the ferrous metals, which gives a burden to all the toxic impact categories. Overall, the main benefits are associated with glass and aluminium recovery.

3.3. Life cycle impact assessment (LCIA) results and interpretation: analysis of the overall WEEE management system in Lombardia Region

Based on the results reported in Section 3.2, the environmental performance of the overall WEEE management system in Lombardia Region in year 2011 was evaluated (Table 9).

WEEE collection and recovery in Lombardia Region in the year 2011 resulted beneficial for almost all the considered impact categories, with the benefits arising from material and energy recovery offsetting the impacts due to the processing of the waste itself. Only for two categories (i.e., human toxicity-cancer effects and freshwater ecotoxicity) the impacts due to the WEEE treatment were not compensated by the benefits associated with material and energy recovery. This is related to the recycling process of the ferrous scraps, as previously explained.

By comparing the individual results of each WEEE category, it is clear that the main benefits to the overall management system are given by the treatment and recovery of TV and monitors (R3), which was the main stream collected in Lombardia Region in the year 2011 (37% of the collected WEEE).

3.4. Results of the sensitivity analysis

As reported in Section 2.3, a sensitivity analysis was performed to understand how the results are influenced by the assumptions about the composition of the R3 category (in terms of percentage of FPDs vs. CRTs) and about the metal substitution ratio.

3.4.1. Percentage of FPDs in the R3 category

The recovery of the R3 category is no more beneficial for the human toxicity (cancer effects) when the mass weight of FPDs exceeds 15%. A worsening of the environmental performance is also observed for the impact categories human toxicity (non-cancer effects), ozone depletion and freshwater ecotoxicity, contrary to what is observed for climate change, mineral and fossil resource depletion and for the CED (Table G.1 of the Additional materials). It must be pointed out that the modelling of the recovery process of FPDs was based on the common practices at the year 2011 and significant improvements in material recovery are expected in the near future. For example, several researches have focused in the last years on the possibility to recover indium from the LCD panels (Fontana et al., 2014; Lee et al., 2013; Zhuang et al., 2012).

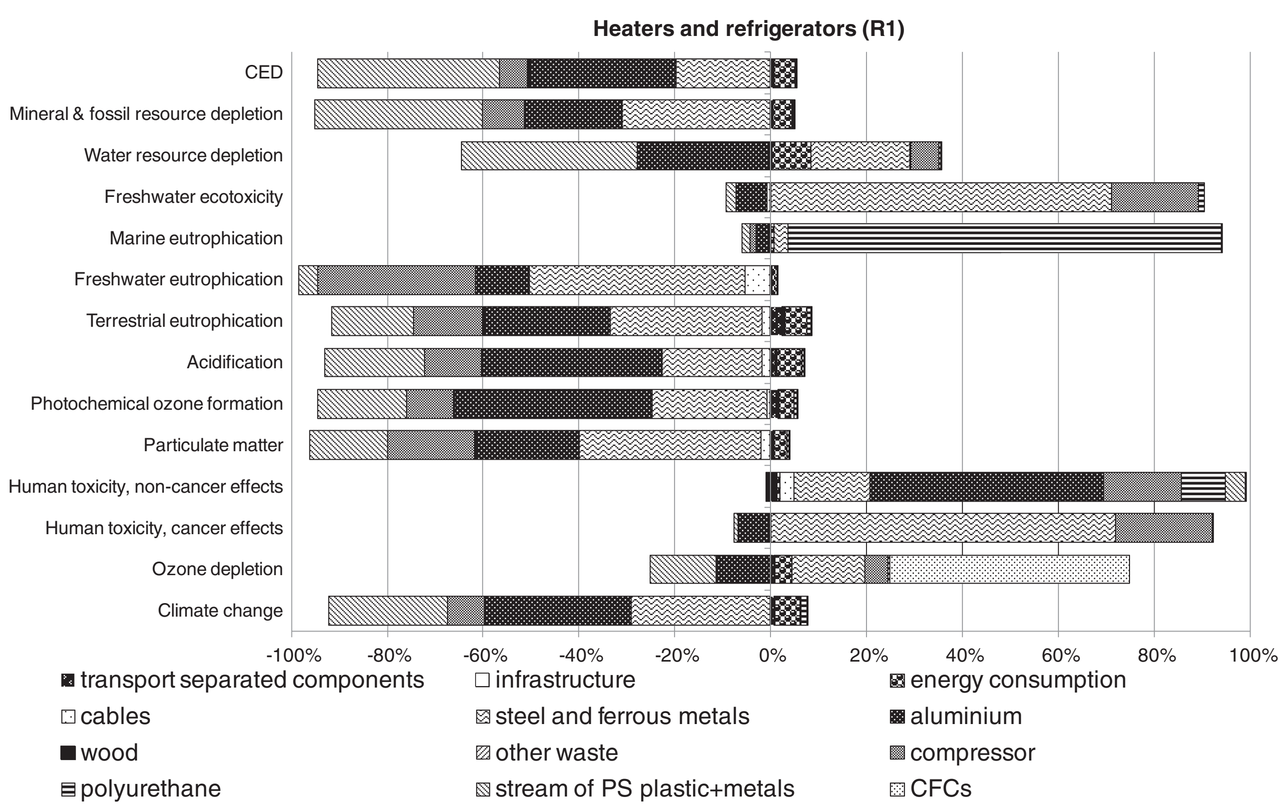

Fig. 2. Contribution analysis of the management system of 1 tonne of R1, R2, FPDs, CRTs, R4 and R5 in Lombardia Region in the year 2011.

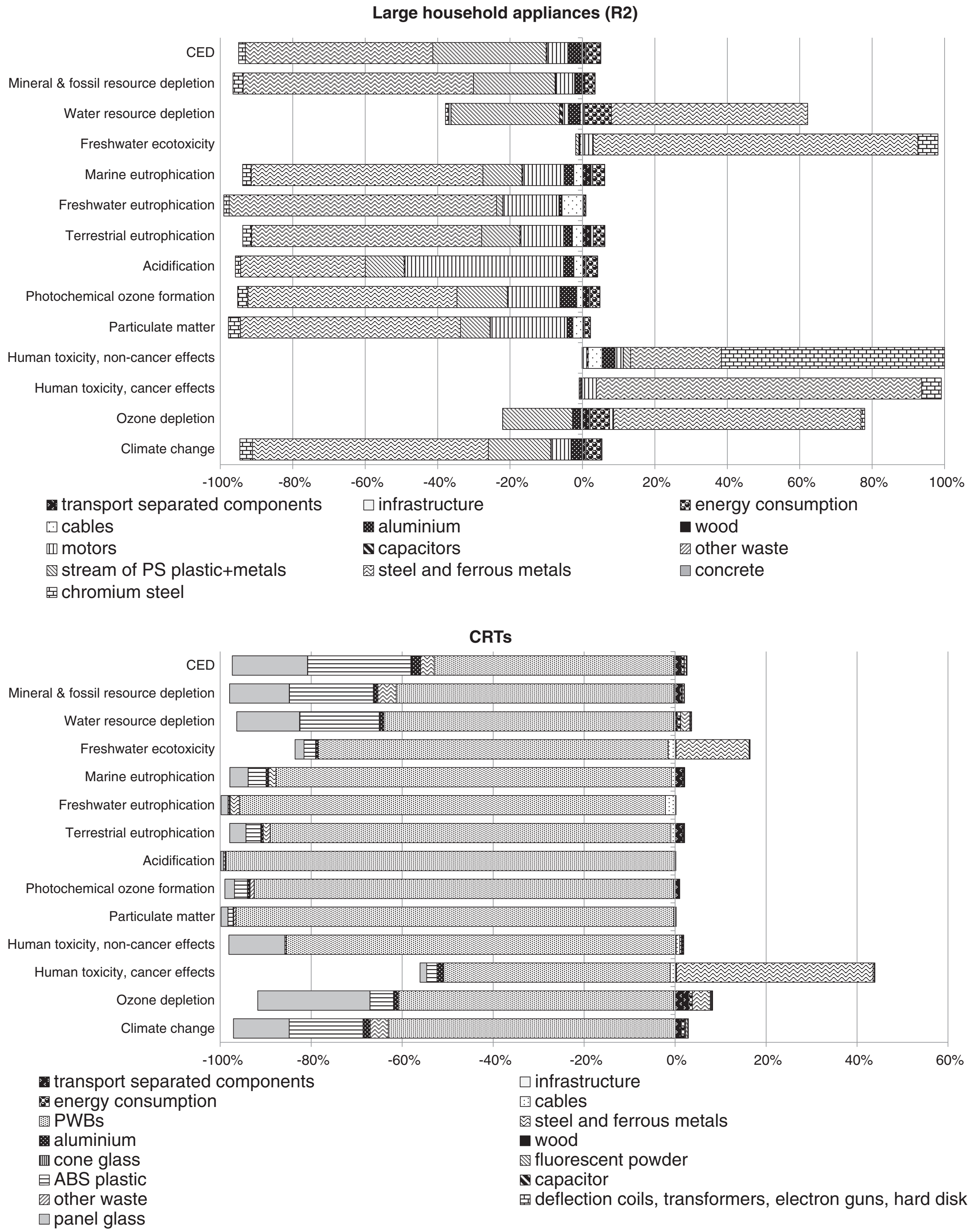

Fig. 2 (*continued*).

3.4.2. Metal substitution ratio

When a substitution ratio equal to 1:0.9 is adopted for aluminium, ferrous metals and chromium steel, the environmental performance of the WEEE management system in Lombardia Region gets worse, as shown in Table G.2 of the Additional materials. A significant worsening was observed for the WEEE categories R1 and R2, for which the impact of the waste treatment process increases by more than 10% for 6 and 12 indicators, and up to +43% for the impact indicator water resource depletion evaluated for the R2 WEEE category. The main reason is the key role played by the ferrous metals and aluminium recovery in the overall burdens/savings, as already extensively discussed. A much more modest influence of the substitution ratio (with an increase of

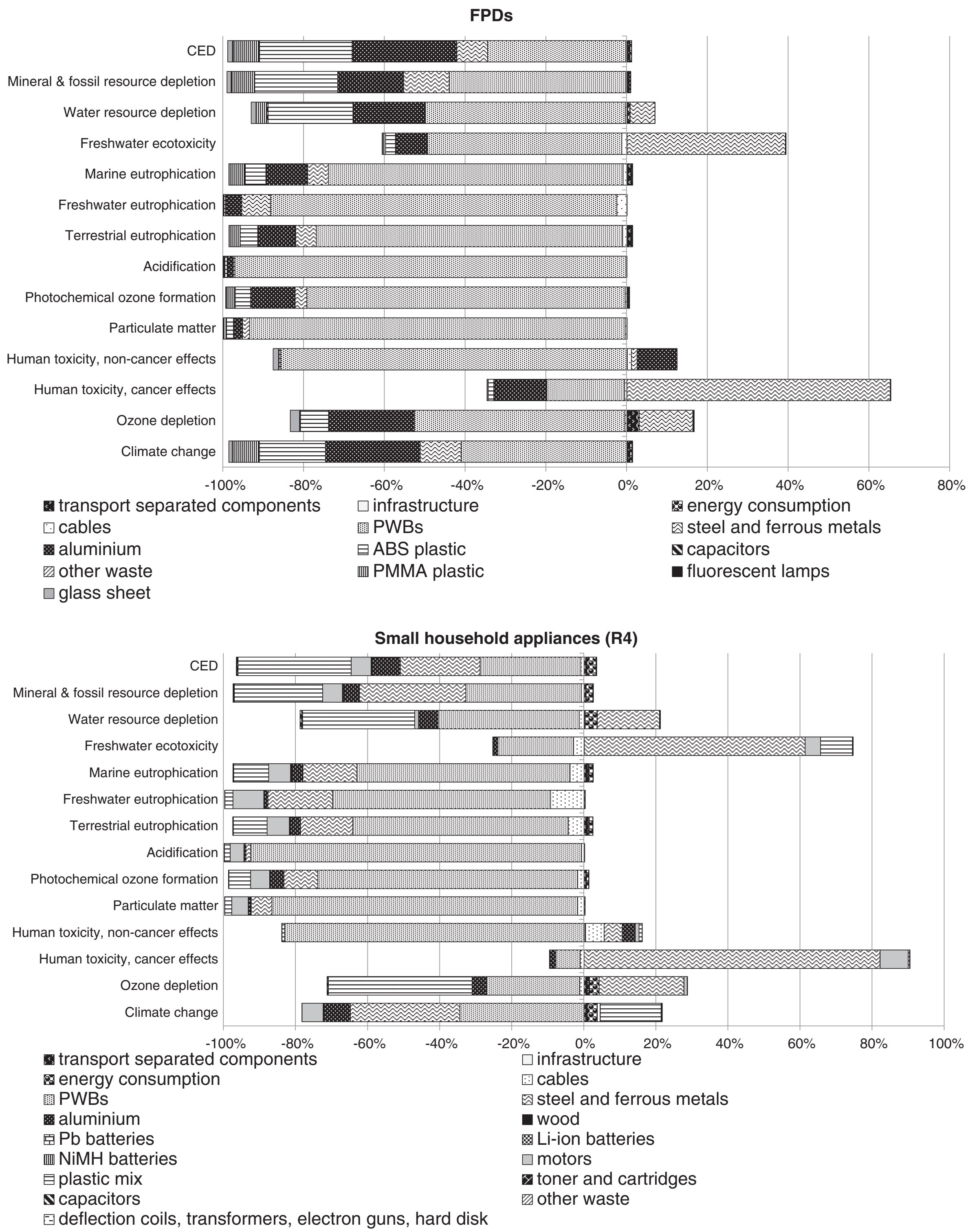

Fig. 2 (*continued*).

less than 7% of the value of the impact indicators) was observed for the other WEEE categories, with the exception of the human toxicity (cancer effect) and the freshwater ecotoxicity for the R5 category, whose values increase by 43% and 82%, respectively. Nevertheless, the treatment and recovery of WEEE are still beneficial overall, with no observed changes in sign (whether positive or negative) of the impact indicators.

3.5. Limitations of the study

The study focuses only on the legal WEEE management system. However, it must be pointed out that every year in Italy, about 700.000 tonnes of WEEE are managed illegally (Ecodom, 2013). A fraction of these wastes are treated with the sole aim to recover the more precious components, such as the metal scraps, without any attention to the

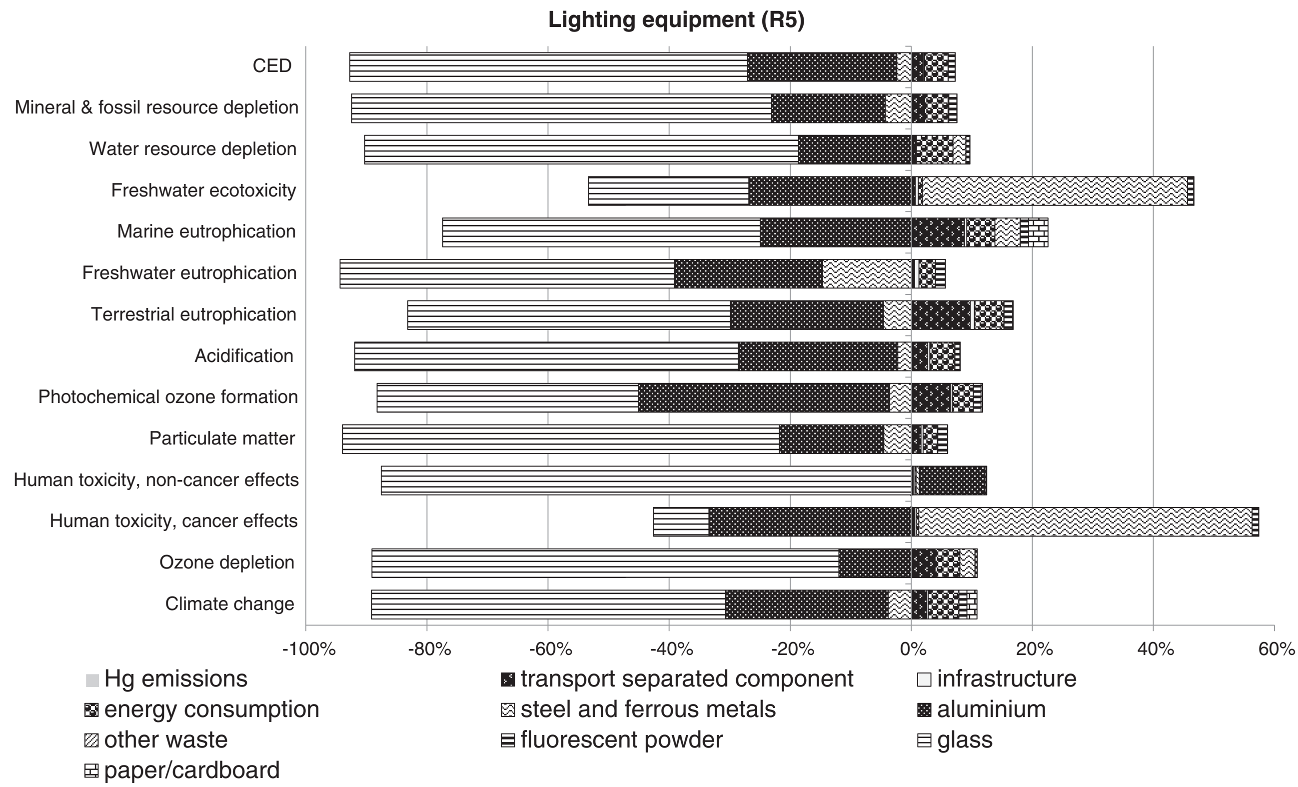

Fig. 2 (*continued*).

impacts on the environment and on the human health. Another fraction is exported to developing countries, where even worse and more dangerous treatment practices are carried out, resulting in significant environmental pollution (Perez-Belis et al., 2015). Since data on these illegal flows are not known, this aspect was not included in our analysis.

Another limitation concerns the assessment of the legal export of some WEEE components to other countries. Based on market conditions, the treatment of cables, motors, power supplies, hard disk, electron guns, deflection coils and transformers can occur in Italy or abroad, especially in China. Because of the lack of information about the treatment processes used in China, the study was based on the assumption that all of these components are treated in Italy.

Despite these limitations, the study showed the complexity of the WEEE treatment and recovery system, which involves several treatment plants at different levels, as a consequence of the great number of components that are separated from the waste. Most of the plants are located inside the Lombardia Region or in Italy, but some are located abroad. As a consequence, the life cycle inventory turned out to be very long and complex, due to the need to acquire a huge amount of data, preferably collected directly at the plants (i.e., primary data) and to assess their

Table 9

Environmental performance of the overall WEEE management system in Lombardia Region in the year 2011 and percentage contribution of each WEEE category to the total results. Values are evaluated considering a collection of 8837 tonnes of R1, 7282 tonnes of R2, 20,069 tonnes of R3 (of which 19,587 tonnes of CRTs and 482 tonnes of FPDs), 9849 tonnes of R4 and 333 tonnes of R5.

Impact category	UM	TOTAL	Heaters and refrigerators (R1)	Large household appliances (R2)	TV and monitors (R3)	Small household appliances (R4)	Lighting equipment (R5)
			Percentage contribution[a]				
Climate change	kg CO_2 eq.	−65,651,553	−12.96%	−8.72%	−66.84%	−11.06%	−0.42%
Ozone depletion	kg CFC-11 eq.	−2	38.75%	15.17%	−130.23%	−22.25%	−1.44%
Human toxicity (cancer effects)	CTUh	50	29.94%	39.79%	−3.50%	33.74%	0.03%
Human toxicity (non-cancer effects)	CTUh	−39	3.95%	3.61%	−96.07%	−11.09%	−0.40%
Particulate matter	kg PM2.5 eq.	−458,352	−1.52%	−1.41%	−82.16%	−14.85%	−0.06%
Photochemical ozone formation	kg NMVOC eq.	−968,157	−3.93%	−2.32%	−78.07%	−15.58%	−0.10%
Acidification	mol H+ eq.	−8,954,763	−0.55%	−0.52%	−84.44%	−14.47%	−0.02%
Terrestrial eutrophication	mol N eq.	−1,713,556	−4.58%	−3.50%	−74.82%	−16.99%	−0.12%
Freshwater eutrophication	kg P eq.	−219,984	−4.82%	−4.57%	−72.63%	−17.91%	−0.07%
Marine eutrophication	kg N eq.	−58,876	146.76%	−9.24%	−193.46%	−43.73%	−0.33%
Freshwater ecotoxicity	CTUe	162,335,984	88.49%	118.30%	−190.50%	83.76%	−0.05%
Water resource depletion	m^3 water eq.	−271,366	−4.00%	2.16%	−84.27%	−13.36%	−0.52%
Mineral and fossil resource depletion	kg Sb eq.	−298,088	−12.03%	−8.61%	−60.99%	−17.99%	−0.37%
Cumulative Energy Demand (CED)	MJ	−1,315,560,618	−13.89%	−7.48%	−60.73%	−17.40%	−0.50%

[a] For each impact category, the percentage contribution of each WEEE category was calculated as "impact of the WEEE category / total impact × 100" and the sum of the five percentage contributions is −100% if the "total" is negative in sign, whereas +100% if the "total" is positive in sign.

quality in order to ensure the reliability of the results obtained. Unfortunately, it was not possible to acquire primary data for all the treatment processes involved. Some processes were, thus, described by relying on the literature. This was the case of the PWBs, whose modelling was based on the EI dataset. Considering the key role that PWBs play in the LCA, a more detailed and case-specific modelling of the process would be required. In some cases, the lack of any information about the treatment or recovery process of a specific component resulted in its exclusion from the system boundaries (for example the brass and the compressor oil), or in the definition of simplified assumptions in order to model those processes. The latter was the case of the PS and ABS plastics. Due to a lack of information, their recycling process was described assuming the same energy consumption, recycling efficiency and substitution ratio of PET. Despite the recycling processes of the three types of plastic are probably very similar, being based on a shredding stage followed by extrusion, the recycling efficiency and the substitution ratio between secondary and virgin material might actually differ. Another limitation of the study concerns the modelling of the landfill for hazardous waste. Due to a lack of data, the disposal of some hazardous components, such as the phosphoric powder containing mercury, was modelled by using the EI dataset which refers to the underground deposit in salt mines located in Germany. This dataset does not include any release in the environment, contrary to what happens in a standard landfill for hazardous waste.

A further investigation would be also required for the polyurethane, which was assumed to be landfilled. Considering its high calorific value, a possible energy recovery should be investigated, based on primary data.

4. Conclusions and recommendations

In this study, the WEEE management system implemented in Lombardia Region (Italy) in the year 2011 was evaluated from an environmental point of view.

The first step of the analysis involved the evaluation of the mass balance of the treatment and recovery system of each of the five WEEE categories. Results showed that steel and glass are the predominant streams of materials arising from the treatment, the first coming mainly from the recovery of the R1, R2 and R4 categories and of the FPDs and the latter from the recovery of the CRTs and of the R5 category. A non-negligible amount of ABS and PS plastics is also recovered, together with small amounts of precious metals, such as gold, silver and palladium.

The environmental performance of the treatment of each WEEE category and of the overall WEEE management system implemented in Lombardia Region in the year 2011 was then evaluated by applying the LCA methodology. The main results are listed in the following points:

1) Considering the overall regional system, the benefits resulting from materials and energy recovery balance the impacts of the treatment processes, with the sole exception of two impact categories (human toxicity-cancer effects and freshwater ecotoxicity). WEEE collection and recovery in the year 2011 allowed avoiding the emission of 65,651 t of CO_2 eq. and the consumption of 1315 TJ eq. The treatment and management system currently implemented in Lombardia Region thus performs well from an environmental point of view, despite that some possible improvements can be suggested, as reported in following point 4;
2) The WEEE categories whose treatment and recovery resulted more beneficial for the environment and the human health are R3 (TV and monitors) and R5 (lighting equipment). This is a useful information to address priorities when a new collection and treatment system for WEEE has to be implemented;
3) The contribution analysis showed that overall the main benefits come from the recovery of the metal fractions, as well as of plastic and glass. Precious metals recovery from PWBs is responsible for the main benefits associated with the recovery of R3 and R4 categories. The key role that metals recovery plays in the environmental performance of the system is confirmed also by Wäger et al. (2011);
4) Concerning the treatment/recovery of the separated components, most of the burdens come from the recycling process for secondary steel production. A reduction of the energy consumption of the smelter and of the direct gaseous emissions, as well as a better management of the furnace slag would improve the performance of the overall WEEE management system. Further improvements might also be achieved with a better control of the CFC incineration process, aimed at the reduction of the emissions at the stack, as well as at the search for an alternative disposal method for polyurethane.

Another interesting aspect arising from the study is related to the treatment of the PWBs and NiMH batteries, which is carried out abroad, since no plants are present in Lombardia Region, nor in Italy. Such components are currently recovered in large-scale centralised pyrometallurgical plants. Some alternative hydrometallurgical processes have been recently studied (Brunori et al., 2013a, 2013b), which would allow to operate on small waste streams at the local scale. Authorities should promote the development of these technologies, in order to move from the pilot scale to full-scale industrial applications.

Concerning the results obtained for the human toxicity-cancer effects and freshwater ecotoxicity category indicators, a more-in-depth analysis could be performed to understand the real role of the secondary steel production to the overall impacts. The characterisation factors used in this study are in fact those derived from the USEtox model (Rosenbaum et al., 2008) as recommended by the PEF guide (EC, 2013). According to the classification of the characterisation models car-ried out by the Joint Research Centre (JRC–EC, 2011L), the USEtox model is classified of level “II/III” (i.e., recommended but in need of some improvements/recommended, but to be applied with caution). Updated characterization factors may be tested, along the lines of recent literature (e.g., Dong et al., 2014; Gandhi et al., 2011), to identify bias in the assessment due to overestimation of metals impact. This could lead to a decrease of the burdens associated with the secondary steel production, where the emission of chromium was identified as a relevant contribution.

A final consideration concerns the proposal of a waste characterisation method based on the outputs rather than on the input of the treatment plants, as it was done in this study. In fact for a very heterogeneous waste stream such as WEEE (and the R4 category in particular), a characterisation based on the outputs of the first treatment plants turned out to be more representative and more relevant from a recovery perspective, than the traditional analysis of the waste input composition.

Acknowledgements

The study was financially supported by Finlombarda for Regione Lombardia.

We wish to thank all the plant operators who have supplied primary data for the LCA.

Appendix A. Supplementary data

Supplementary data to this article can be found online.

References

Allegrini, E., Vadenbo, C., Boldrin, A., Astrup, T.F., 2015. Life cycle assessment of resource recovery from municipal solid waste incienrayion bottom ash. J. Environ. Manag. 151, 132–143.
Andrea, A., Andersen, O., 2010. Life cycle assessment of consumer products — are they consistent? Int. J. Life Cycle Assess. 15, 827–836.
Andreola, F., Barbieri, L., Corradi, A., Ferrari, A.M., Lancellotti, I., Neri, P., 2007. Recycling of EOL CRT glass into ceramic glaze formulations and its environmental impact by LCA approach. Int. J. Life Cycle Assess. 12 (6), 448–454.

Bartl, A., 2014. Ways and entanglements of the waste hierarchy. Waste Manag. 34, 1–2. Betts, K., 2008. Producing usable materials from e-waste. Environ. Sci. Technol. 42, 6782–6783.
Bovea, M.D., Ibanez-Fores, V., Gallardo, A., Colomer-Mendoza, F.J., 2010. Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study. Waste Manag. 30, 2383–2395.
Brunori, C., Cafiero, L., De Carolis, R., Fontana, D., 2013a. Tecnologie innovative per il recupero/riciclo di materie prime da RAEE: il progetto Eco-innovazione Sicilia. Energia Ambiente Innovazione 5, 78–85 (in Italian).
Brunori, C., Fontana, D., De Carolis, R., Pietrantonio, M., Pucciamati, S., Guzzinati, R., Torelli, G.N., 2013b. Request for italian patent: Progetto idrometallurgico per il recupero di materiali dalle schede elettroniche (in Italian).
Centro di Coordinamento RAEE, 2011. Dossier sulla gestione dei rifiuti da apparecchiature elettriche ed elettroniche in Lombardia Anno 2011. www.cdcraee.it (latest access 8-2-2013 (In Italian)).
Cui, J., Forssberg, E., 2003. Mechanical recycling of waste electronic and electronic equipment: a review. J. Hazard. Mater. B99, 243–263.
Cui, J., Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: a review. J. Hazard. Mater. 158, 228–256.
Guinée, J.B., Gorrée, M., Heijungs, R., Huppe, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H.,, van Duin, R., M.A.J., Huijbregts, 2002. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Kluwer Academic Publishers; Dordrecht, The Netherlands.
Decreto Legislativo, 2005. Attuazione delleDirettive 2002/95/CE, 2002/96/CE e 2003/108/CE, relative alla riduzione dell'uso di sostanze pericolose nelle apparecchiature elettriche ed elettroniche, nonchéallo smaltimento dei rifiuti (in Italian).
Decreto Ministeriale, 2007. n.185. Istituzione e modalità di funzionamento del registro nazionale dei soggetti obbligati al finanziamento dei sistemi di gestione dei rifiuti di apparecchiature elettriche ed elettroniche (RAEE), costituzione e funzionamento di un centro di coordinamento per l'ottimizzazione delle attività di competenze dei sistemi collettivi e istituzione del comitato d'indirizzo sulla gestione dei RAEE, ai sensi degli articoli 13, comma 8, e 15, comma 4, del decreto legislativo 25 luglio 2005, n. 151. (in Italian) (25 Settembre).
Dong, Y., Gandhi, N., Hauschild, M.Z., 2014. Development of comparative toxicity potentials of 14 cationic metals in freshwater. Chemosphere 112, 26–33.
Eccola JRC – EC, 2011. Recommendations for Life Cycle Impact Assessment in the Europe-an context - based on existing environmental impact assessment models and factors. http://eplca.jrc.ec.europa.eu/ EUR 24571 EN -.
Ecodom, 2013. Ecodom premia la vincitrice del concorso "raeeporter social" e accende i riflettori sui flussi illegali di raee. http://www.ecodom.it/it-it/Press-area/Comunicati-stampa/Comunicati-2013/Dettaglio-Comunicato-2013/ArtMID/673/ArticleID/3050 (latest access 16-3-2015 (in Italian)).
Ekvall, T., Assefa, G., Bjorklund, A., Erikson, O., Finnveden, G., 2007. What life-cycle assess-ment does and does not do in assessments of waste management. Waste Manag. 27, 989–996.
European Commission, 2002. Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the Restriction of the Use of Certain Hazardous Sub-stances in Electrical and Electronic Equipment.
European Commission, 2003. Directive 2003/108/EC of the European Parliament and of the Council of 8 December 2003 Amending Directive 2002/96/CE on Waste Electrical and Electronic Equipment (WEEE).
European Commission, 2014. htttp://epp.eurostat.ec.europa.eu/portal/page/portal/waste/key waste stream/waste electrical electronic equipment weee (latest access 12/05/ 2014).
European Commission, JRC (Joint Research Center), (IES) Institute for Environment and Sustainability (Eds.), 2010. ILCD Handbook: General Guide for Life Cycle Assessment and Detailed Guidance (Available at: http://lct.jrc.ec.europa.eu/assessment/publication (accessed 15 March 2012)).
European commission, 2013. EU PRODUCT ENVIRONMENTAL FOOTPRINT (PEF) GUIDE published April 9th 2013 as annex II to the Commission Recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.
Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., 2009. Recent developments in life cycle assessment. J. Environ. Manag. 91, 1–21.
Fontana, D., Forte, F., De Carolis, R., Grosso, M., 2014. Indium recovery from waste liquid crystal displays. Proceedings SUM 2014, Second Symposium on Urban Mining, 19–21 May 2014, Bergamo, Italy.
Gandhi, N., Diamond, M.L., Huijbregts, M.A.J., Guinée, J.B., Peijnenburg, W.J., van de Meent, D., 2011. Implications of considering metal bioavailability in estimates of freshwater ecotoxicity: examination of two case studies. Int. J. Life Cycle Assess. 16 (8), 774–787.
Grosso, M., Rigamonti, L., Brambilla, V., Luglietti, R., Falbo, A., 2012. Progetto Gerla. Supporto tecnico-scientifico in materiale di valutazione del ciclo di vita (LCA) applicata a sistemi di gestione di rifiuti urbani in Regione Lombardia. Relazione n.2. Analisi LCA del sistema di gestione dei rifiuti urbani della Lombardia: situazione attuale e scenari evolutivi (In Italian).
Habuer, Nakatani, Jun, Moriguchi, Yuichi, 2014. Time-series product and substance flow analyses of end-of-life electrical and electronic equipment in China. Waste Manag. 34, 489–497.
Hischier, R., Wager, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling system for waste electrical and electronic equipment (WEEE). Environ. Impact Assess. Rev. 25, 525–539.
Hischier, R., Weidema, B., Althaus, H.J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. Implementation of Life Cycle Impact Assessment Methods. Ecoinvent report N. 3, v 2.2. Swiss Centre for Life Cycle Inventories, Dübendorf.
ISO 14040:2006, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework.
ISO/TR 14049, 2000. Environmental Management – Life Cycle Assessment – Example of Application of ISO 14041 to Goal and Scope Definition to Inventory Analysis. Johansson, J.G., Bjorklund, A.E., 2009. Reducing life cycle environmental impacts of waste electrical and electronic equipment recycling. J. Ind. Ecol. 14 (2), 258–269.
Kikuchi, Y., Hirao, M., Oookubo, T., Sasaki, A., 2014. Design of recycling system for poly(methyl methacrylate) (PMMA). Part 1: recycling scenario analysis. Int. J. Life Cycle Assess. 19, 120–129.
Koffler, C., Florin, J., 2013. Tackling the downcycling issue — a revised approach to value-corrected substitution in life cycle assessment of aluminium (VCS 2.0). Sustainability (Switzerland) 5, 4546–4560.
Lee, C.H., Jeong, M.K., Kilicaslan, M.F., Lee, J.H., Hong, H.S., Hong, S.J., 2013. Recovery of indium from used LCD panel by a time efficient and environmentally sound method assisted HEBM. Waste Manag. 33 (3), 730–734.
Li, J., Lu, H., Guo, J., Xu, Z., Zhou, Y., 2007. Recycle technology for recovering resources and products from waste printed cuircuit boards. Environ. Sci. Technol. 41, 1995–2000.
Lu, L.T., Wernick, I.K., Hsiao, T.Y., Yu, Y.H., Yang, Y.M., Ma, H.W., 2006. Balancing the life cycle impacts of notebook computers: Taiwan's experience. Resour. Conserv. Recycl. 48, 13–25.
Park, P.J., Tahara, K., Jeong, I.T., Lee, K.M., 2006. Comparison of four methods for integrat-ing environmental and economic aspects in the end-of-life stage of a washing ma-chine. Resour. Conserv. Recycl. 48, 71–85.
Perez-Belis, V., Bovea, M.d., Ibanez-Fores, V., 2015. An in-depht literature review of the waste electrical and electronic equipment context: trends and evolution. Waste Manag. Res. 33, 3–29.
Rigamonti, L., Grosso, M., Sunseri, M.C., 2009. Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. Int. J. Life Cycle Assess. 14 (5), 411–419.
Rigamonti, L., Grosso, M., Giugliano, M., 2010. Life cycle assessment of sub-units composing a MSW management system. J. Clean. Prod. 18, 1652–1662.
Rigamonti, L., Falbo, A., Grosso, M., 2013a. Improvement actions in waste management systems at the provincial scale based on a life cycle assessment evaluation. Waste Manag. 33, 2568–2578.
Rigamonti, L., Falbo, A., Grosso, M., 2013b. Improving integrated waste management at the regional level: the case of Lombardia. Waste Manag. Res. 31 (9), 946–953.
Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Köhler, A., Larsen, H.F., MacLeod, M., Margni, M., McKone, T.E., Payet, J., Schuhmacher, M., van de Meent, D., Hauschild, M.Z., 2008. USEtox — The UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in Life Cycle Impact Assessment. Int. J. Life Cycle Assess. 13 (7), 532–546.
Swiss Center for Life cycle Inventories, 2010. Ecoinvent: The Life Cycle Inventory Data, Version 2.2.
Tsydenova, O., Bengtsson, M., 2011. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag. 31, 45–58.
Tuncuk, A., Stazi, V., Akci, A. l, Yazici, E.Y., Deveci, H., 2012. Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling. Miner. Eng. 25, 28–37.
Van Oers, L., de Koning, A., Guinée, J.B., Huppes, G., 2012. Abiotic Resource Depletion in LCA — Improving Characterisation Factors for Abiotic Resource Depletion as Recom-mended in the New Dutch LCA Handbook. Road and Hydraulic Engineering Institute.
Wäger, P.W., Hischier, R., Eugster, M., 2011. Environmental impacts of the Swiss collection and recovery systems for waste electrical and electronic equipment (WEEE): a follow-up. Sci. Total Environ. 409, 1746–1756.
Zhuang, X., He, W., Li, G., Huang, J., Ye, Y., 2012. Material separation from waste liquid crystal displays using combined physical methods. Pol. J. Environ. Stud. 21 (6), 1921–1927.