ENVIRONMENTAL IMPACT CAUSED BY THE WASTE OF ELECTRICAL AND ELECTRONIC EQUIPMENT: AN ITALIAN SCENARIO

IMPACTULASUPRA MEDIULUI CAUZAT DE DEŞEURILEDE ECHIPAMENTE ELECTRICE ŞI ELECTRONICE: UN SCENARIU ITALIAN

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Abstract. *Nowadays, some of the highest amounts of waste is caused by the waste of electrical and electronic equipment (WEEE). The main reasons are related to the increasing demand in consumption and in reducing the life of electrical and electronic equipment (EEE). Our paper focuses on a case study which aims to develop a quantitative analysis of the WEEE flow based on a scenario implemented by an Italian collector from the Emilia Romagna region, specifically the city of Bologna. This scenario was evaluated based on the Life Cycle Assessment methodology, in terms of environmental and human health impacts, using the CML2001 and ReCiPe methods, available in GaBi software tool. Following the LCA software application, the impacts generated by the proposed scenario highlighted a negative influence especially on Fossil Fuel Depletion, Marine Ecotoxicity Potential and Global Warming Potential. It was found that the amount of generated emissions causeshighimpacts to material resources and fresh waters.*

Key words: consumption, electrical and electronic equipment, environmental impacts, life cycle assessment, waste

Rezumat. *Unele dintre cele mai mari cantități de deşeuri sunt reprezentate astăzi de deşeurile de echipamente electrice şi electronice (DEEE). Principalele cauze ale generării DEEE sunt legate de creşterea consumului şi reducerea duratei de viață a echipamentelor electrice şi electronice (EEE). Această lucrare analizează, din punct de vedere cantitativ, un studiu de caz bazat pe un scenariu ce vizează un flux al DEEE implementat de un colector italian din regiunea Emilia Romagna, în particular oraşul Bologna. Scenariul a fost evaluat prin prisma metodologiei evaluării ciclului de viață (ECV), în ceea ce priveşte impactul asupra mediului şi sănătății umane folosind metodele CML2001 şi ReCiPe, disponibile în instrumentul software GaBi. În urma aplicării ECV, impacturile generate de scenariul propus au evidențiat o influență negativă, în special asupra resurselor fosile, a potențialului de*

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ecotoxicitate marină şi potențialului de încălzire globală. De asemenea s-a constatat că emisiile generate în cantități din ce în ce mai mari generează impacturi ridicate asupra resurselor materiale şi resurselor de apă dulce.

Cuvinte cheie: consum, echipamente electrice şi electronice, impactul asupra mediului, evaluarea ciclului de viață, deşeuri

INTRODUCTION

The exponential increase in the consumption of electronic and household products in our society, together with their relatively accelerated wear are the main contributors to the increase of the electrical and electronic equipment (EEE) waste stream (Elia and Gnoni, 2013). The management of the Waste of Electrical & Electronic Equipment (WEEE) becomes a major and almost permanent challenge. WEEEmanagement has also become a prominent global problem (Bonoli *et al.*, 2018; Clark *et al.*, 2019; Ongondo *et al.*, 2011). In 2014, 41.8 million tonnes of WEEE were collected globally. These wastes consist of a very wide range of electrical and electronic products that contain high levels of incorporated carbon due to extraction and processing. Their environmental impact is exacerbated by the elimination of electrical and electronic products before the end of their useful life (Cole *et al.*, 2019).

WEEE, defined as „waste electrical and electronic equipment" by EU Directive 2002/96/EC (EC Directive 96, 2002), generates a considerable ecological pressure in the waste management cycles, mainly due to their high content of potentially hazardous substances (De Felice *et al.*, 2014; Gnoni and Elia, 2013; Ordoñez and Rahe, 2013). The electronic wastes contain a variety of hazardous materials such as cadmium, lead, mercury, polychlorinated biphenyls and brominated flame retardants (Widmer *et al.*, 2005), which can generate considerable risks to both humans and the environment, if they are not properly treated. They also contain potentially valuable materials such as ferrous and non-ferrous metals, glass, plastics and rare and critical minerals (Buchert *et al.*, 2012), which, if recovered, represent a latent economic opportunity (Zhang and Xu, 2016).

Directive 2012/19/EU on WEEE imposes the obligation to collect a large part of the end-of-life products by producers of EEE placed on the market. This obligation is promoted to encourage product development and to minimize WEEE containing toxic components, as manufacturers try to reduce the cost burden on producer responsibility through eco-design (Gottberg *et al.*, 2006). The management of WEEE is therefore of increased interest, both at the level of institutional and industrial organizations with priority over the end-of-life stage (End-of-Life, EoL) (Bandyopadhyay, 2008; OECD, 2009). Given this context, a number of studies were published in an attempt to analyze the potential impact of WEEE management systems on climate change using life cycle assessment (LCA) - a well-established methodologyoften applied to assess the potential impactsof products and product systems on the environment and on human health –described either fully or partially through the so-called „carbon footprint" (Clark *et al.*, 2019).

Life cycle assessment (LCA) is a methodology used to quantify the environmental impact of products, considering all stages of production and consumption, from the production of raw materials to the end of life, including all intermediate stages. Companies can rely on LCA to identify, evaluate, consolidate, interpret and disseminate environmental impact data generated by their activities. Therefore, in the management sciences, LCA is known as an *environmental management accounting tool* (Bicalho *et al.*, 2017). The LCA methodology was developed to analyze and quantify the emissions related to a product or service during their entire life cycle (from *cradle to grave*) (Zampori *et al.*, 2016). The main feature of the LCA approach is to include a wide range of environmental concerns, such as climate change, toxic effects, depletion of material resources. Also, it has a holistic character that prevents the transfer of the environmental problem from a compartment to another, and also prevents the solution of a certain problem that deteriorates elsewhere in the life cycle (Marcelino-Sabada *et al.*, 2017). The LCA also provides valuable information that allows managers to make decisions designed to improve the environmental performance of their processes, products and / or services (Hossain *et al.*, 2016). Although this methodology does not target individual material products, it remains useful as a quality management tool for environmental factors because it facilitates the identification of the source of a potential problem or concern, optimizes the use of resources and manages the waste produced, thus contributing to decision making (Chen *et al.*, 2010; Comăniță *et al.*, 2018; Ghinea *et al.*, 2017; Simion *et al.*, 2017).

Some studies have combined LCA with other environmental systems analysis techniques to gain a more comprehensive understanding of the system performance. Material flow analysis (MFA) combined with LCA approaches were used by Wäger *et al.* (2011), Biganzoli *et al.* (2015), Turner *et al.* (2016), to evaluate the ecological performance of WEEE management systems in Switzerland, Lombardy Region of Italy, Cardiff, United Kingdom, respectively. An approach based on LCA integrating multicriteria analysis was presented by de Souza *et al.* (2016) in their study on the sustainability of the WEEE management systems in Brazil, which considered social and economic performance, as well as the environment.

Our paper focuses on the assessment of environmental and human health impactsgenerated by WEEE considering a scenario used by an Italian collector from the Emilia Romagna region, the city of Bologna, with a view on extending the life cycle of potentially recoverable materials. The performed analyses are based on a case study regarding the management system of WEEE implemented by the collector during 2015. The main aim of the study is to identify the negative environmental impacts using LCA methodology.

MATERIAL AND METHOD

WEEE management system in Italy

According to Decree 151/2005, available from 12 November 2007, the national management system of WEEE in Italy, the producers, distributors and local authorities play an important role in the collection of EEE. The producers are organized in the so-called „collective systems” that fulfill the obligations mentioned in the decree regarding transportation, costs, respectively treatment and recovery of WEEE under conditions of free competition (Ollio, 2011). Table 1 shows the territorial spread of WEEE collection centers to each region in Italy, considering the collection centers and collection rates for 2014 and 2015.

Table 1

Territorial dissemination of WEEE collection centers in Italy (Centro di Coordinamento RAEE, 2015)

Region	Collection centers (2014)	Collection centers (2015)	Collection rate in the centers 2015/2014	Other collection rates 2015	Collection centers per 100.000 residents 2015	Collection rate in the center per 100.000 residents 2015/2014
Valle d'Aosta	26	26	0.00%	0	20	0.23%
Piemonte	291	292	0.34%	27	7	0.62%
Liguria	75	79	5.33%	11	5	5.91%
Lombardia	826	841	1.82%	75	8	1.52%
Veneto	458	455	-0.66%	52	9	-0.67%
Trentino Alto Adige	209	215	2.87%	8	20	2.48%
Friuli Venezia Giulia	153	162	5.88%	10	13	6.08%
Emilia Romagna	**365**	**362**	**-0.82%**	**32**	**8**	**-0.91%**
Total - Northern Region	**2,403**	**2,432**	**14.76%**	**2230**	**90**	**15.26%**
Toscana	192	198	3.13%	32	5	3.07%
Umbria	69	69	0.00%	2	8	0.22%
Marche	116	121	4.31%	3	8	4.47%
Abruzzo	46	51	10.87%	11	4	11.07%
Lazio	176	186	5.68%	36	3	5.29%
Total - Center Region	**599**	**625**	**23.99%**	**84**	**28**	**24.12%**
Campania	241	257	6.64%	13	4	6.79%
Molise	32	34	6.25%	1	11	6.72%
Basilicata	57	57	0.00%	1	10	0.31%
Puglia	126	123	-2.38%	16	3	-2.38%
Calabria	81	90	11.11%	1	5	11.33%
Sardegna	168	182	8.33%	6	11	8.37%
Sicilia	94	106	12.77%	17	2	12.83%
Total - South Region	**799**	**849**	**42.72%**	**55**	**46**	**43.97%**

The „collective systems” are managed by the Coordination Center (CdC), and financed by producers and can be either specialized on a certain type of EEE products or they can collect all types of EEE products. According to the Decree 49/2014 and the dispositions of the Coordination Center Code, each collective system should ensure that the electronic waste is collected by the national collection centers. The amount of WEEE that a collective system should gather is directly proportional to the quantity of EEE marketed each year by the producers that adhere to the collective system.

The increasing activity of the Coordination Center has been confirmed by an 8% rise in the amount of WEEE collected through the collective systems in 2015. The northern and center region of Italy have recorded the highest increase rate of total WEEE collected. In the northern region for example, the rate of collected WEEE increased by 6.23%, with 6.2% more than in 2014, Piemont and Emilia Romagna areas registering the highest increase (Centro di Coordinamento RAEE, 2015). The Emilia Romagna region has a population of about 4.5 million people and a total waste value registered at 16.6 million tons in 2014 (Pini *et al.*, 2018). It was rated to second place in Italy in 2015 concerning the rate of collected WEEE, with an average increase of 5.33 kg per resident (fig. 1). On the other hand, in comparison to 2014, the number of collection centers has decreased from 365 to 362 (Centro di Coordinamento RAEE, 2015).

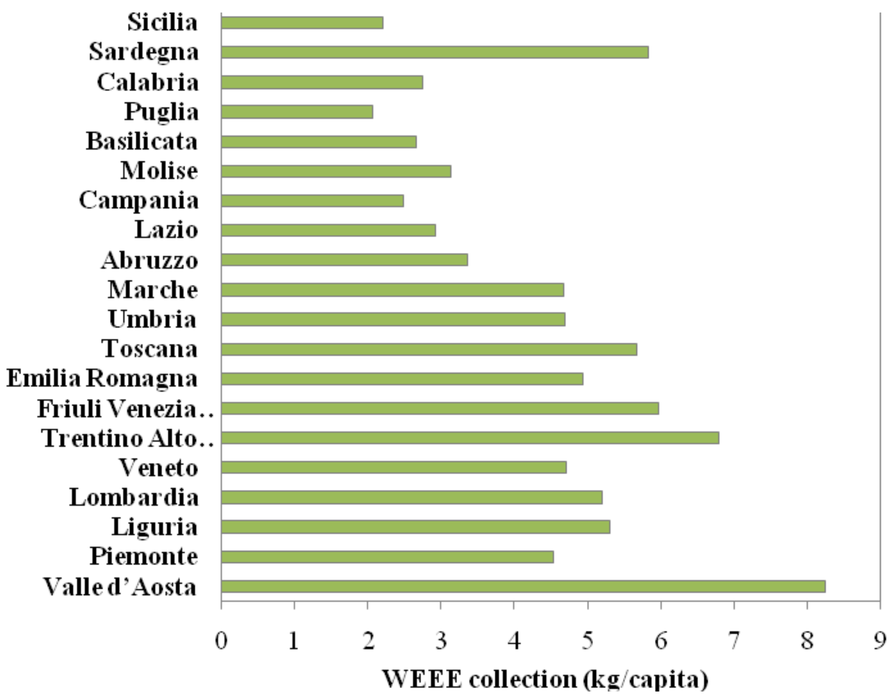

Fig. 1 The quantities of WEEE collected from different regions of Italy in 2015 (adaptedafter Centro di Coordinamento RAEE, 2015)

System boundaries and functional unit

The system boundaries were established based on a scenario which includes 3 main stages: transport and collection, temporary storage withsorting of waste and final storage, and asan output,materials recovery and reuse (fig. 2). The scenario is used in the activity of an Italian WEEE collector which aims to minimize the consequences of waste production and management by focusing on the field of WEEE and applying the principle of „proximity". It also has a production process that follows the „Metal

Recycling" concept, which refers to the extension of a product's theoretical infinite life by recovering and applying important components such as precious metals. Once it has been evaluated through a life cycle perspective, the scenario can help both the producer and the consumer to improve the consumption throughout the processes, which will lead to lower environmental impacts. Within the considered scenario, the functional unit is represented by the quantity of waste collected during a collection campaign carried out in 2015. The amount of WEEE collected during the campaign was estimated at 3000 kg.

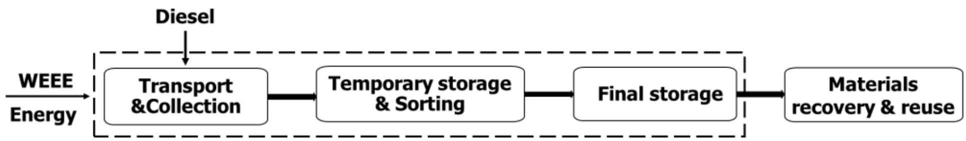

Fig. 2 System boundaries for WEEE system at the collector

Data collection and modelling

The inventory data collection is the most intense and time-consumingphase of all phases involved in LCA. This includes the collection of quantitative and qualitative data for each unit process in the system. The collected information was used in GaBi software.

Life cycle impact assessment

According to ISO 14040, the life cycle assessment of a product or process is an environmental management technique which identifies the flows of energy, materials and waste, as well as their impact on the environment throughout the entire life cycle of the product (Gaudrealt *et al.*, 2010; Ghinea and Gavrilescu, 2010). The environmental impact assessment stage comprises three elements defined by the SETAC nomenclature: classification, characterization and weighting (Teixeira *et al.,* 2015).

The environmental impact assessment studies (input and output data for the scenario) were implemented using the GaBisoftware, educational database 2016 developed by PE International GmbH. GaBi is a modular system that includes plans, processes, flows, and their functions, which is why the system can be considered with a clear and transparent structure. The databases used by the system are independent of each other and they are responsible for saving all the information related to an analyzed system (Ghinea and Gavrilescu, 2010; Pieragostini *et al.*, 2012). GaBi software calculates the potential impact on the environment, as well as other significant quantities of a plan-based product system.

Both CML 2001 and ReCiPe methods were selected and applied for the life cycle impact assessment. The CML 2001 method was developed by the Institute of Environmental Sciences, Leiden University, The Netherlands, being an impact assessment method that limits quantitative modeling in the beginning stages of the situation in question, which helps defining a clear record. The results are grouped into categories according to common mechanisms (for example, climate change or ecotoxicity). Normalization factors for CML 2001 are available for the Netherlands, Western Europe, EU and worldwide. They are calculated by means of the total emissions of substances and of the characterization factors per substance. The ReCiPemethod is used for life cycle impact assessment (LCIA) and calculates 18 intermediate indicators and 3 final indicators. Intermediate indicators focus on unique environmental issues, such as climate change or acidification, whereas the final indicators concern the impact on the environment at three higher levels of aggregation (e.g. the effect on human health, biodiversity and the lack of resources). The impact categories identified in the LCA study according to each method are included in table 2.

Table 2

Categories of environmental impact and indicators used by CML 2001 and ReCiPe methods in Life Cycle Assessment

Environmental impact categories	
CML 2001 method	**ReCiPe method**
Abiotic Depletion Potential (ADPe) *Abiotic Depletion Potential (fossil)* (ADPf) *Acidification Potential* (AP) *Eutrophication Potential* (EP) *Freshwater Ecotoxicity Potential -* (FAETP) *Global Warming Potential* (GWP) *Human Toxicity Potential* (HTP) *Marine Ecotoxicity Potential* (MAETP) *Terrestrial Ecotoxicity Potential* (TEco) *Ozone Depletion Potential* (ODP) *Halogenated Compounds (HC)* *Photochemical Ozone Creation Potential (POCP)*	*Agricultural Land Occupation (ALO) [species.yr]* *Climate change Ecosystems (CcEco) [species.yr]* *Climate change Human Health deterioration (CCHh) [DALY]* *Fossil Depletion (FD) [$]* *Freshwater Ecotoxicity* (*FAET) [species.yr]* *Freshwater Eurtrophication (Feut) [species.yr]* *Human Toxicity (HT) [DALY]* *Ionizing Radiation (IR) [DALY]* *Marine Ecotoxicity (MAET) [species.yr]* *Metal Depletion (MD) [$]* *Natural land transformation (NLT) [species.yr]* *Ozone Depletion (Odp) [DALY]* *Particulate matter Formation (PmF) [DALY]* *Photochemical Oxidant Formation (POF) [DALY]* *Terrestrial acidification (TA) [species.yr]* *Terrestrial ecotoxicity (Teco) [species.yr]* *Urban land occupation [species.yr]*

RESULTS AND DISCUSSIONS

The application of the LCA methodology using GaBi software demonstrated that the impact generated by the analyzed scenario, considering CML 2001 method, has a strong influence on the Marine Ecotoxicity Potential (MAETP), Abiotic Depletion Potential (fossil) (ADPf) and Global Warming Potential (GWP), with relative contributions of 56.6%, 17.1% and 12.4%, respectively for each impact category (fig. 3).

The Marine Ecotoxicity Potential (MAETP) refers to the effects of a compound on organisms living in water and it is usually determined for organisms representing the three trophic levels: vertebrates (fish), invertebrates (crustaceans like *Daphnia* spp.) and plants (algae). The impact category Marine Ecotoxicity Potential (MAETP) manifests itself to a greater extent on the environment than the other impact categories, and the hierarchy of environmental impact given by the proposed scenario is: MAETP >ADPf> GWP 100 years > AP > POCP > HTP > EP > FAETP > TETP>ADPe> ODP. This result is based on the fact that the disassembly and transport stages result in a large amount of emissions affecting marine trophic levels.

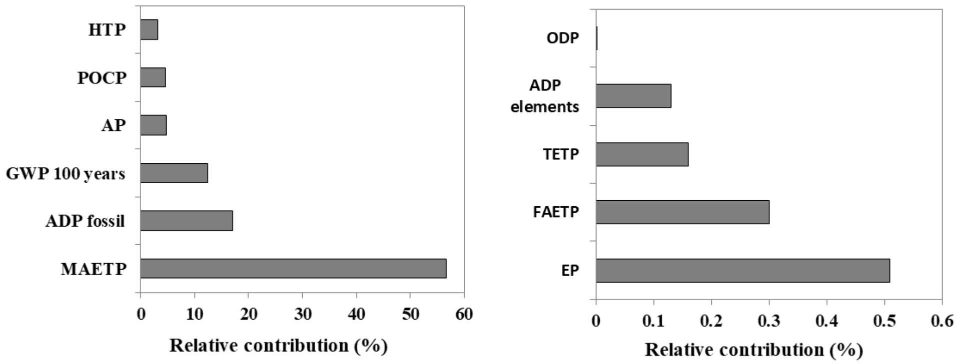

Fig. 3 Relative contribution (%) of environmental impact categories identified using CML 2001 method

The results obtained by applying the ReCiPe method (fig. 4) showed that the indicator with the highest impact resulted from the analyzed scenario system is Fossil Depletion (FD) (99.2%). This indicator is related to the use of fossil fuels, which provide a valuable source of energy and raw materials throughout the WEEE management cycle implemented by the collector. Therefore, based on the results obtained by applying the ReCiPe method, the following hierarchy of impact categories for the collector management system was established: FD >> MD >>CCHh> HT >PmF>CCEco> ALO >> ALO > MAET >POF > TA > IR >Teco>Feut> FAET >Odp.

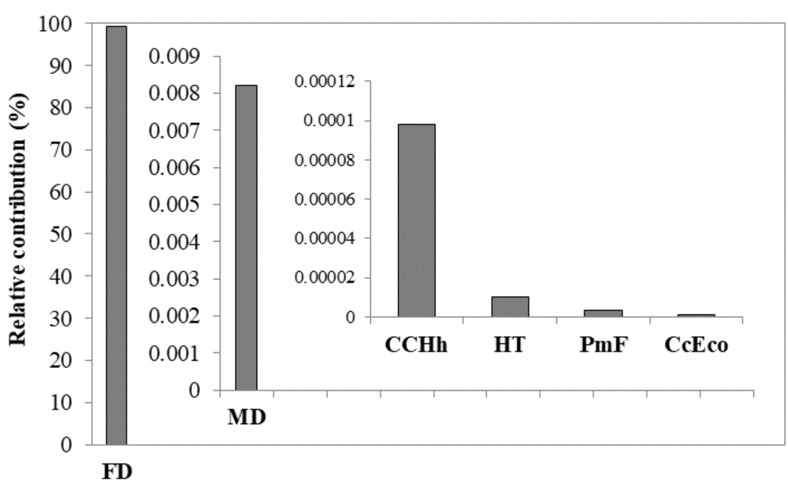

Fig. 4 Relative contribution (%) of environmental impact categories identified using ReCiPe method

The impact of the emissions (%) generated following the implementation of the management system proposed within the collector strategy, for the evaluation of the current waste management system is presented in figure 5. It can be observed that the emissions (%) are mainly causing impacts to resources (including material and energy resources) and fresh water. This is due to materials consumption and the diesel used in the transport stage which contains nitrogen and metals that have a direct impact on the freshwater. The third highest amount of emissions is in the aerial environment (0.33%) and it is caused by carbon monoxide (CO) and particulate matter (PM) pollutants. Sea water and industrial soil are less affected, given the low % of emissions resulted, of less than 0.001% (data not included in graphs). On the other side, a positive impact could be observed in the case of agricultural soil (-5.43E-09%).

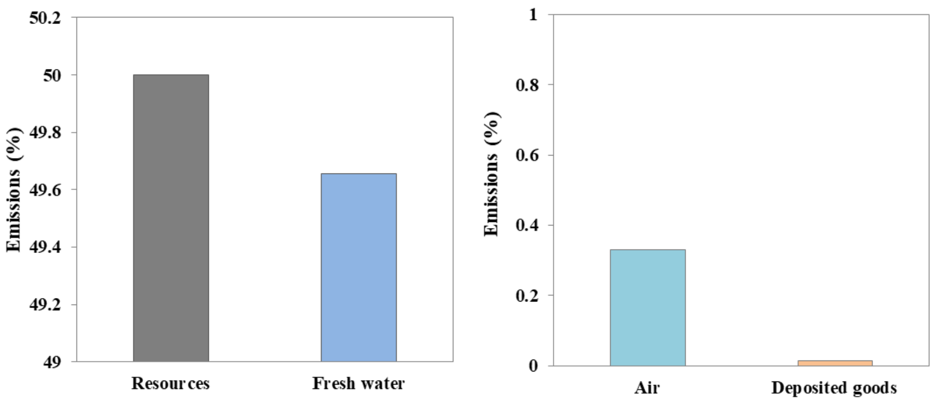

Fig. 5 Emissions (%) generated following the implementation of the analyzed scenario in the environmental compartments

Related to the consumption (%) (fig. 6) generated following the implementation of the analyzed scenario, we could observe that the highest consumption is given by the electricity used within the storage&sorting stage (79.75%), followed by transport & collection stage (20.23%). Diesel consumption is estimated as very low during the transport & collection stage (0.002%).

The recycling of EEE-type waste, after proper treatment in special installations, can generate considerable benefits, such as reducing the exploitation of non-renewable raw materials, reducing the storage places (landfills) and creating secondary materials which can be used immediately for recycling, with the obvious reduction of the availability time of the material itself. Thus, the reuse of the secondary materials recovered contributes to reducing the environmental impact of WEEE, the creation of new jobs and the generation of profit.

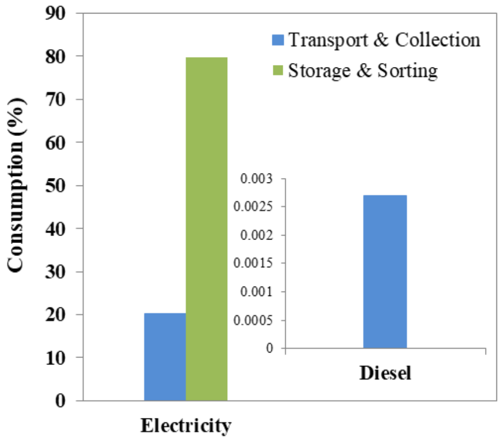

Fig. 6 Consumption (%) generated following the implementation of the analyzed scenario

CONCLUSIONS

The WEEE management system implemented by the Italian collector has been evaluated from an environmental point of view using the LCA methodology. The 4-steps scenario was analyzed using Gabi software and by applying the CML 2001 and ReCiPe methods.

The data obtained through the LCA showed that the disassembly of WEEE and their transport generates the highest impact given the amount of emissions to resources and in the water compartment. In addition, it was found that these stages contribute to climate change, positive impact values being obtained for the Global Warming Potential (GWP) indicator (12.4%), when the CML 2001 method was applied. The hierarchy of the environmental impacts determined in the case of the applied scenario is MAETP >ADPf> GWP 100 years > AP > POCP > HTP > EP > FAETP > TETP>ADPe> ODP. When we applied the ReCiPe method, we could observe a major shift as compared to CML 2001 method. The indicator with the highest impact resulted from the analyzed scenario using ReCiPe method was Fossil Depletion (FD) (99.2%). Considering the consumption (%) within the proposed scenario, the highest valuewas given by the electricity used within the temporary storage & sorting stage (79.75%).

Such studies are of major importance in the context of the continuous development of the electrical and electronic equipmentindustry, the generation of waste and the scale of climate change. The LCA analysis carried out in this study can be a key tool for developing environmental policies, sustainable management of raw material and energy resources, optimizing the WEEE management systems and making decisions in line with sustainable development principles.

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