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Comparative Analysis of Three WEEE Management Scenarios Based on LCA Methodology: Case Study in the Municipality of Iasi, Romania

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Abstract: The increasing consumption of electrical and electronic equipment (EEE), correlated with the fast innovation pace in this field, generates a large amount of annual waste. The current established management practices cannot keep up with it, and the results are of increased significance given the negative effects on the environment and human health. Thus, the current study aimed to analyze the environmental impact of three different scenarios of waste electrical and electronic equipment (WEEE) management, following population awareness campaigns regarding its collection in the Municipality of Iasi, Romania. Data processing was carried out considering Life Cycle Assessment (LCA) methodology with the established functional unit for each scenario according to the collected amount. The results were quantified using the CML2001 and ReCiPe methods and showed that the highest environmental impact was obtained for scenario II (S2) (1.59×10^{-7} pers. equiv. using the CML2001 method and 32.7 pers. equiv. using the ReCiPe method), while the lowest for scenario I (S1) (6.42×10^{-8} pers. equiv. using the CML2001 method and 13.8 pers. equiv. using the ReCiPe method). The process with the highest contribution to the total environmental impact was the collection stage for all scenarios, with the exception of scenario S2, in which case the highest value was generated for the landfill process following the application of the ReCiPe method (39.93%). The current study provides value to a critical issue in the environmental area and supports the development of sustainable WEEE management processes.

Keywords: e-waste; Life Cycle Assessment; environmental impact; energy; waste management; recovery

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1. Introduction

The rapid development of electrical and electronic equipment (EEE) over the last decades, together with the incapacity of current e-waste management systems to keep up with its disposal, generates serious concerns worldwide [1]. E-waste, also known as waste electrical and electronic equipment (WEEE), contains both hazardous and non-hazardous substances that can cause critical effects on the environment and human health. These consequences can be generated during different life cycle stages of the WEEE management system, from the collection of the waste up to its disposal and recycling [2]. Hazardous substances and materials contained by e-waste are heavy metals, plastics, brominated flame retardants, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), etc. [3–6]. Heavy metals such as Pb, Hg, Cd and As [7] can inhibit plant growth and negatively affect animal and human health since they are able to bioaccumulate in living organisms [8,9]. It is thus difficult and costly to remove them [9]. Some elements have a higher impact than others. For example, lithium and fluorine from Li-ion batteries can contribute the most to negative environmental effects (80–90%), while phosphorous has a lower contribution (20%) [10].

Furthermore, it is not only household electronic and electrical devices that can end up as waste. The renewable energy sector, namely that of solar power, has been raising concerns over the increase in waste photovoltaic panels, which is estimated to reach 60–78 million tons by 2050 [11]. Thus, efficient WEEE management systems are important in order to avoid the negative effects of improper landfilling as well as to minimize the environmental burden of the management system itself.

Unfortunately, although WEEE generation is a significant environmental issue, only 66% of the world has implemented e-waste policies. Since the enforced rules, programs and rate of WEEE recycling differ around the world, it can be difficult to compare the amounts of generated and collected WEEE. Furthermore, it is not only the collected and recycled WEEE that should be considered, but also WEEE that is informally collected, recycled outside of the take-back systems, and illegally exported, but their quantification is an even greater challenge [12]. The ineffectiveness of global WEEE management systems is also proven by the issue of large exports from the developed to the developing countries that are even less equipped to tackle e-waste, causing health problems to the native population and environment [13].

The best enforced WEEE legislation and management systems are in countries or regions such as Japan and countries of the European Union, while most developing countries do not even have a WEEE management system [14]. In Italy for example, the collection system is based on five categories of e-waste, while in Norway there are fourteen total WEEE categories that are followed, four being additional to the ones established by the EU directives [15,16]. In Sweden, although some WEEE management processes are delegated to the private sector, the main responsibility is attributed to the local authorities, which manage all household wastes. By comparison, most European countries have in place a system that assigns the main responsibility to the producers, which are organized in Producer Responsibility Organizations (PROs) [16]. Therefore, although the informal recycling of WEEE can cause major issues in the environment and human health, formal recycling requires a careful analysis in order to understand the key points that can be improved from a sustainability perspective. Furthermore, the negative environmental impacts of WEEE management can be attributed not only to informal recycling, but also to an inefficient application of a formal system. It is thus important to optimize the processes included in WEEE management systems in order to reduce the overall environmental burden.

A pivotal player in the WEEE management scheme is represented by the collection centers, where the pathway of an EEE is decided, whether it is reuse, remanufacturing, repair or recycling ([17]). These institutions or organizations are required to abide by standards and laws. In the European Union, the current EU legislation, namely Directive 2002/06/EC and Directive 2012/19/EU, imposed restrictions regarding the use of certain toxic substances in EEE, established WEEE collection targets and introduced the Extended Producer Responsibility (EPR), which placed the responsibility for the whole e-waste life cycle management in the hands of producers [18,19].

Life Cycle Assessment (LCA) is an established methodology for the analysis of the environmental performance of products and processes and can be used as an input in decision-making regarding the choice of waste management systems or strategic decisions regarding the priority of resource use [20]. LCA enables the identification of opportunities that can bring improvements in the quality of the environment. This methodology is standardized at the international level, and considers the Ecoinvent database [21], which is one of the most effective and complete databases for identifying and evaluating environmental impacts. The LCA methodology facilitates the identification of environmental burdens of a product or system and ultimately enables problem solving and the optimization of key sustainability issues, including WEEE management. The LCA methodology is also recommended at the level of the European Union for quantifying the environmental impact of products and processes [22]. So far, a number of significant research studies have addressed this area. The LCA analysis of the waste treatment steps and recycling of lithium batteries [23], e-waste recycling for metal recovery from high-grade WEEE [24], the end-of-life stage of cooking hoods [25], WEEE management in a full-scale Italian facility [26], the WEEE transportation network in the Reggio Emilia district of Northern Italy [18], the e-waste management system in Bologna, Municipality of Emilia Romagna region [14], and the remanufacturing of computers [27] have been covered.

Although developed countries from the European Union such as Germany and Sweden have no problem with meeting the established-by-law collection targets, in Romania this is still an issue [28]. The sustainability of the Romanian WEEE management system can definitely be improved, either in terms of increasing the collected amounts of e-waste and/or optimizing the established collecting practices. Carbon footprint of WEEE management systems in EU countries such as Italy, Sweden, Germany, Bulgaria, as well as Romania were calculated recently for the time period 2007–2014 [28]. The results showed that all these countries, including Romania, have reduced their carbon footprint. The study also highlighted that out of these five countries, Romania occupies the second place among the largest exporters of WEEE outside its territory [28]. The current study aims to analyze the environmental performance of three WEEE management scenarios in the Municipality of Iasi, Romania using LCA methodology. This research study thus highlights key processes and resources where the environmental burden can be improved for WEEE management in Romania, with applicability to other countries as well that follow the same system. This is performed using two different established LCA methods and GaBi Education software. The carried-out research adds value through the comparison of three different scenarios (S1, S2, S3) of WEEE management. Moreover, two of the analyzed scenarios (S2, S3) include a phase of raising awareness among the local population regarding the importance of WEEE collection, a process which to our knowledge has not been yet included in LCA studies of WEEE management.

The main objectives set for the LCA analysis are: (1) the qualitative and quantitative analysis of WEEE flow in the Municipality of Iasi, Romania; (2) the development of management alternatives for WEEE and the evaluation of their impact taking into account the amount and composition of the collected e-waste; (3) the evaluation of the impact on the environment generated by the implementation of WEEE management systems by applying the LCA methodology; (4) carrying out a comparative analysis of some WEEE management systems using the CML2001 and ReCiPe methods; (5) the identification of an environmentally favorable WEEE management alternative.

2. Materials and Methods

2.1. Life Cycle Assessment Methodology

The environmental impact analysis of WEEE management scenarios in the Municipality of Iași, Romania was carried out using the LCA methodology (Figure 1) following the four stages as established by ISO 14040 and ISO 14044 standards [22,29]:

- goal and scope definition—consists of the establishment of a reference that will be considered for the overall analysis in order to follow a clear pathway;
- inventory analysis—consists of data gathering and categorizes the available information into inputs or outputs for the analyzed system;
- impact assessment—represents the phase in which the results concerning the generated environmental impact are obtained;
- interpretation—the phase in which the results are interpreted in a clear, concise and accurate manner according to the established goal and scope in order to be further used by researchers, policy and decision makers.

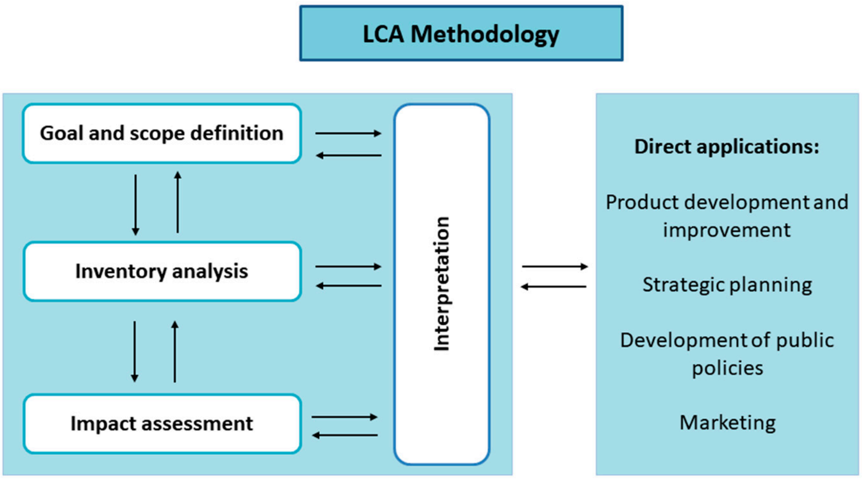


Figure 1. Stages of the Life Cycle Assessment (LCA) methodology.

2.2. Scope and Functional Unit

The functional unit is represented by the WEEE amount collected during population awareness campaigns in the Municipality of Iasi, Romania in 2018–2019, respectively: for scenario I, S1—20,818 kg, for scenario II, S2 and scenario III, S3—29,691 kg. All the input and output data regarding these three analyzed scenarios (energy consumption, raw materials, emissions, etc.) were related to the established functional units (Figure 2).

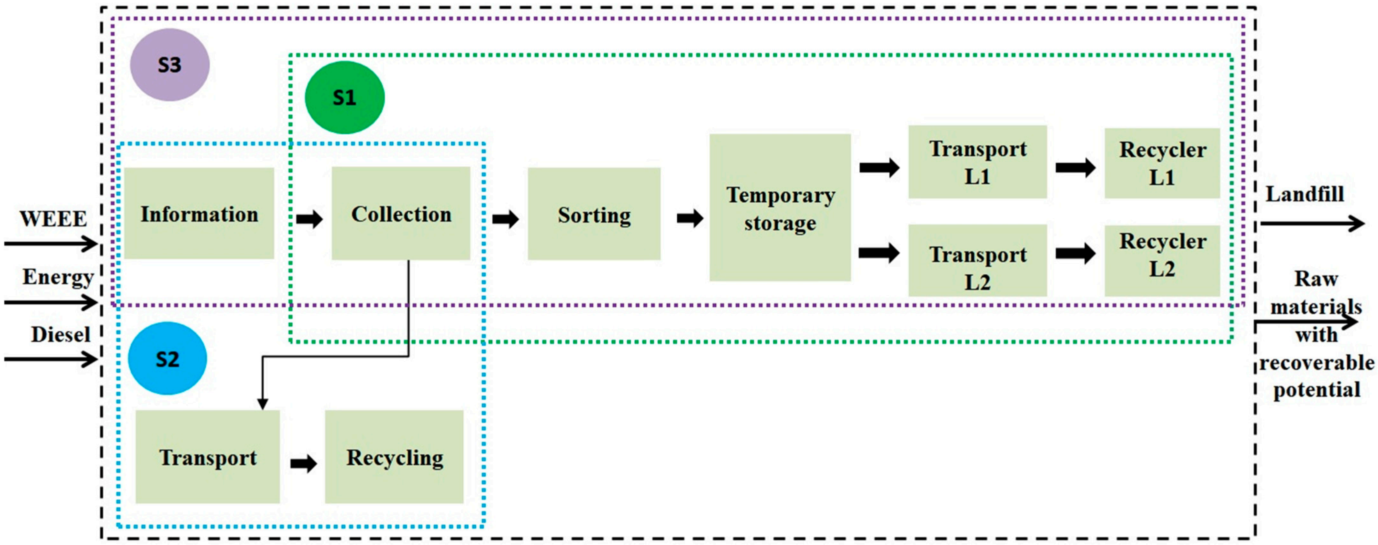


Figure 2. System boundaries of WEEE management systems—all considered scenarios (L1—recycling location Apahida, Romania; L2—recycling location Jilava, Romania).

2.3. System Description

The system boundary defines which processes will be included in or excluded from the system. Often, a combination of different criteria must be used to properly define the boundaries. In terms of system characteristics, the cutoff approach was applied, in which the flow of recyclable parts is considered only up to the process of their recovery, excluding their upcycling or reuse into new products [30]. This means that, in the current study, a cradle-to-cradle approach of the system was defined for the analyzed scenarios, with the first process included in the system being the collection step for scenario I (S1), while the information step was further included for scenarios II (S2) and III (S3). The cradle-to-cradle approach involves the recovery of materials from a waste product through recycling in a closed-loop system [31].

The stages included in the three scenarios are as follows:

- Information—involves the activity of education and awareness through several communication channels. In this sense, the following steps are usually taken: the creation of promotional material layout, printing, press conferences, the distribution of materials by volunteers or specially authorized companies, press layouts, radio, TV and the 1:1 approach.
- Collection—consists of taking over WEEE from individuals and legal entities following requests received in local and national call centers, loading them into specially authorized cars, as well as transporting them to the temporary storage depot.
- Transport—the distance traveled by the van loaded with WEEE to the unloading point, temporary storage or recycling storage.
- Sorting—the handling–storage procedure according to the legal provisions based on categories and codes of electrical and electronic equipment waste.
- Temporary storage—involves keeping WEEE in specially authorized warehouses in order to collect some quantities and send them to recyclers.
- Recycling—can be manual or mechanical. The mechanical method involves the procedure of shredding or breaking. Unlike the manual method, the mechanical method cannot effectively recover precious metals. For this reason, disassembly is manually performed in many cases. This represents the operations of disassembly, processing, and the recovery of waste [32]. In Romania, recycling facilities do not represent the standard known model. They usual perform e-waste preparation for the further recycling and recovery of some parts, and disposal activities [33].

The stages were chosen according to the waste management situation in recent years. In scenario I (S1), the amount of waste collected without the population being informed and updated with the new WEEE management rules was considered. Currently, the implicit organization applies new standards by which it brings new changes in the stages of the management system. Due to the changes in legal provisions, the organization in partnership with the local authorities built a center for the collection and temporary storage of WEEE. The extent of WEEE recovery and the cost of recycling required the transport of WEEE to different recyclers based on categories, and groups were transported in batches of 10–12 tons.

Scenario II (S2) considered 4 stages including a stage of informing the population with the aim of collecting a larger amount of waste compared to S1. In this scenario, it was also considered that the sorting stage was carried out within the transport stage at the time of unloading waste to the recycler. The information stage was taken into account from the desire to meet the collection targets imposed by the European Union, namely 45% of the number of electrical and electronic products sold on the market in a specific year for the time period 2017–2020 [34], and to increase the collection rate of WEEE removed from use. This stage involved a campaign that took place over a period of two weeks, being carried out only through the print media and radio. Due to the lack of local infrastructure, the quantity taken from individuals and legal entities was loaded unsorted into a single haul destined for a single recycler.

Scenario III (S3) was the most complex scenario and was applied by the organization included in the study for taking over the responsibility of producers, within the scope of the Municipality of Iași. Local partners in this campaign were: Iași City Hall, the Local Sanitation Operator, Environmental Protection Agency, the Environmental Guard Commissariat and the student leagues. Attempts to make costs and consumption more efficient have led to the finding that information, education and awareness can contribute in the long term to increasing the WEEE collection rate. The information phase was provided by flyers, on the street and in mailboxes, print and online media, radio and the Facebook page. The information campaign took place two weeks before the collection campaign. The involvement of student organizations had a positive impact on the population. They were trained and divided into teams, managing in this way the approach of a large number of people. The advantage of this campaign was the fact that the organizers made available to citizens a free WEEE pick-up service from home by calling or by placing orders online and directly with volunteers. In the same campaign, fixed points were set up where citizens could bring used or non-functional electrical equipment. To encourage and stimulate the population to conscientiously dispose of this equipment, a raffle with fixed prizes or bonuses was also organized. The amount collected during this campaign was 29,691 kg.

2.4. Life Cycle Inventory

The life cycle inventory phase (LCI) consists of the collection of input (natural resources, primary materials, types of energy, products) and output information (emissions, energy, products and by-products) for all processes included in the system boundaries. In the current study, several different sources of data were used, including databases incorporated in GaBi Education software such as Ecoinvent, collected data from the accredited collector RoRec Association and two local recyclers. Input data regarding the collected WEEE amount per category considered in the study is summarized in Table 1. In terms of energy, the electricity consumption was 11,033 MJ for S1, 18,782 MJ for S2 and 12,968 in the case of S3. As far as the transport component is concerned, diesel consumption was equal for S1 and S2, 2500 kg, while S3 had a quantity of 1500 kg.

Table 1. LCI data for the analyzed scenarios of WEEE management through LCA methodology.

Input Data	Amount per Scenario (%)		
	S1	S2	S3
Air (air-conditioned)	1.59	1.59	1.59
Boiler household	0.64	0.64	0.64
Computer case	1.81	1.81	1.81
Cooking machines	8.41	8.43	8.43
Electric hobs	0.04	0.04	0.04
Hoods	0.03	0.03	0.03
Keyboard and mouse	0.10	0.10	0.10
Kitchen appliances	1.61	1.62	1.62
Large appliances for waste heat	0.43	0.40	0.40
Measuring device	0.64	0.64	0.64
Microwave ovens	2.32	2.32	2.32
Monitors CRT	1.66	1.66	1.66
Monitors LCD	0.19	0.19	0.19
Other IT equipment	0.07	0.07	0.07
Personal care appliances	0.67	0.67	0.67
Photocopiers	2.09	2.09	2.09
Printers	0.51	0.52	0.52
Radio sets	0.15	0.15	0.15
Refrigerating appliances	40.35	40.25	40.25
Television CRT	13.08	13.12	13.12
Television LCD	1.72	1.72	1.72
Vacuums cleaner	1.11	1.11	1.11
Washing machines	20.71	20.76	20.76
Writing machines	0.06	0.06	0.06

2.5. GaBi Education Software

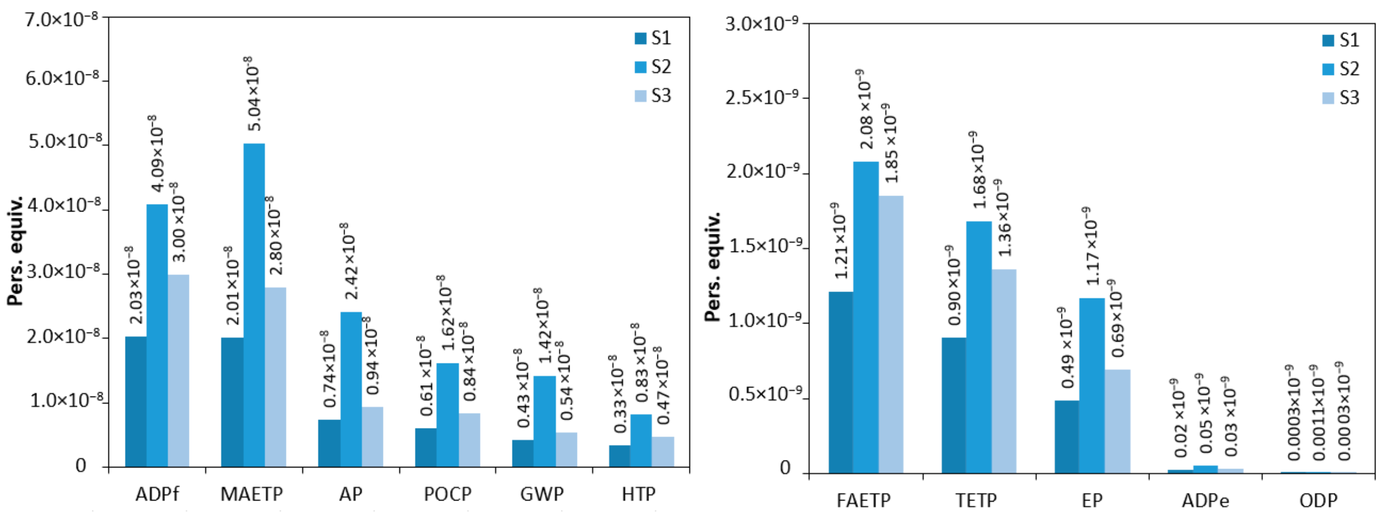
The inventory data (input and output data for the used scenarios) were processed in GaBi Education software. GaBi Education software is a modular system that includes plans, processes, flows, as well as their functions, which is why the system can be considered with a clear and transparent structure [35]. The databases used by the system are independent of each other, being responsible for saving all the information related to an analyzed system [36].

In order to evaluate the impact of the scenarios proposed as WEEE management alternatives according to the LCA methodology, two specific evaluation methods with different categories of impact were chosen to highlight the favorable scenario from the point of view of environmental protection. The CML2001 and ReCiPe methods were considered due to the annually updated database and the fact that they are the most used and recognized methods in Europe and the United States.

3. Results

3.1. Life Cycle Assessment of the Environmental Impact of WEEE Management System in Romania Using CML2001 Method

The results of the environmental impact assessment of S1, S2 and S3 using CML2001 method are depicted in Figure 3.



(**a**) (**b**)

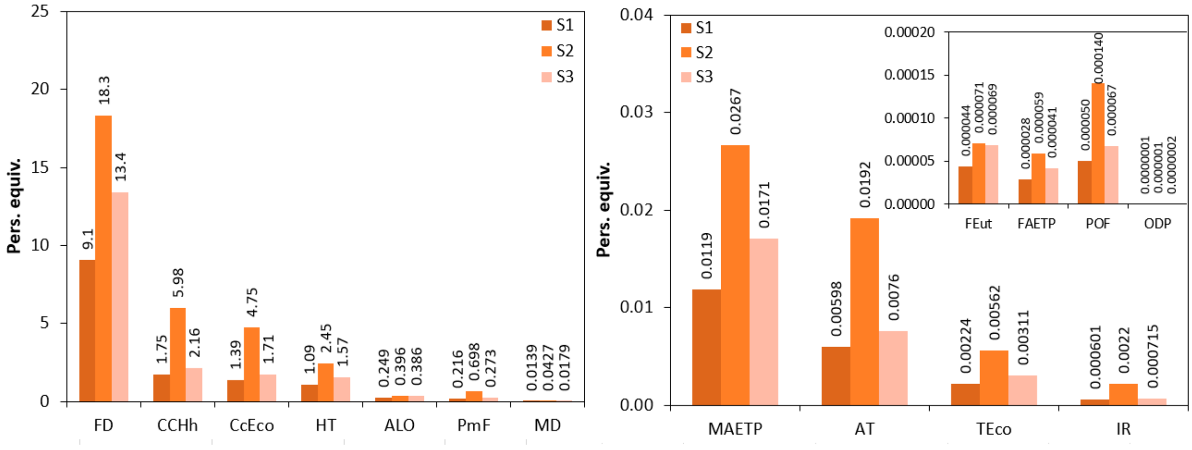
Figure 3. Environmental impact assessment of WEEE management system in the Municipality of Iasi, Romania using CML2001 method—all scenarios: (**a**) ADPf: abiotic depletion—fossil; MAETP: marine aquatic ecotoxicity potential; AP: acidification potential; POCP: photochemical ozone creation potential; GWP: global warming potential—100 years; HTP: human toxicity potential; (**b**) FAETP: freshwater aquatic ecotoxicity potential; TETP: terrestrial ecotoxicity potential; EP: eutrophication potential; ADPe: abiotic depletion—elements; ODP: ozone layer depletion potential, steady state.

It can be observed that the obtained impact category values for S1 and S3 followed the hierarchy: ADPf > MAETP > AP > POCP > GWP > HTP > FAETP > TETP > EP > ADPe > ODP. In the case of S2 though, the highest value was generated for the impact category marine aquatic ecotoxicity potential (MAETP).

The total generated environmental impact identified by the CML2001 method was higher for S2 (1.59×10^{-7} pers. equiv.), followed by S3 (8.98×10^{-8} pers. equiv.) and finally, S1 (6.42×10^{-8} pers. equiv.). The same pattern was identified for all analyzed impact categories, however. Furthermore, the obtained results show positive values for each impact category. Positive impacts show the negative effects on the environment and human health, while negative values highlight the benefits that are brought in terms of sustainability [24].

3.2. Life Cycle Assessment of the Environmental Impact of WEEE Management System in Romania Using ReCiPe Method

The results of the environmental impact assessment of S1, S2 and S3 using ReCiPe method are depicted in Figure 4.



(a) (b)

Figure 4. Environmental impact assessment of WEEE management system in the Municipality of Iasi, Romania using ReCiPe method—all scenarios: (**a**) FD: fossil depletion; CCHh: climate change human health, including biogenic carbon; CcEco: climate change ecosystems, including biogenic carbon; HT: human toxicity; ALO: agricultural land occupation; PmF: particulate matter formation; MD: metal depletion; (**b**) MAETP: marine ecotoxicity potential; AT: terrestrial acidification; TEco: terrestrial ecotoxicity; IR: ionizing radiation; FEut: freshwater eutrophication; FAETP: freshwater ecotoxicity; POF: photochemical oxidant formation; ODP: ozone depletion.

The obtained impact category values for S1 followed the hierarchy: FD > CCHh > CcEco > HT > ALO > PmF > MD > MAETP > AT > TEco > IR > FEut > FAETP > POF > ODP.

In the case of S2, the order was slightly different: FD > CCHh > CcEco > HT > PmF > ALO > MD > MAETP > AT > TEco > IR > POF > FEut > FAETP > ODP.

In S3, the hierarchy was: FD > CCHh > CcEco > HT > ALO > PmF > MD > MAETP > AT > TEco > IR > FEut > POF > FAETP > ODP.

The results show that for all the analyzed system boundaries, the highest impact was obtained for the fossil depletion (FD) impact category. Its observed environmental impact value was in fact significantly higher than the rest of the impact categories. It was approximately three times higher than the values generated for climate change human health (CCHh), climate change ecosystems (CcEco) and human toxicity (HT). Additionally, for all analyzed scenarios, the lowest environmental impact was identified in case of ozone depletion (ODP) category. Similar to the results obtained using CML2001 method, for all analyzed impact categories through the ReCiPe method, the total generated impact value is higher for S2 (32.7 pers. equiv.), followed by S3 (19.6 pers. equiv.) and lastly, by S1 (13.8 pers. equiv.). The results also show positive values for each impact category, proving that there are only negative effects on the environment and human health.

3.3. Comparative Analysis of Life Cycle Assessment Results and Possibilities for System Improvement

Although the issues concerning WEEE management have been known and addressed for more than a decade, and given the advancement of the LCA methodology in recent years, a review study by Withanage and Habib [37] analyzing the application of Life Cycle Assessment in this area identified only 31 studies, out of which most were focused on the recycling and recovery processes. Only a small part of the known literature is concentrated on the full cycle from collection to recycling. This highlights a serious gap in the research of the sustainability of WEEE management [37]. It is also important to note that LCA is the methodology for environmental impact assessment, which has been mostly applied from all available methods for WEEE management analysis [38].

Raising awareness regarding the importance of proper WEEE disposal is very important as studies show that this can have a considerable impact on the efficiency of waste management [39]. In Romania, there is, for example, a lack of information concerning the existence and location of WEEE collection centers, as well as the environmental legislation attributed to e-waste management [33]. Since most published articles evaluated the sustainability of WEEE management from collection to recycling or only focused on the recycling part, in the current study one of our objectives was to focus through our research on the processes preceding the recycling stage. Furthermore, we also included in the system boundaries a stage considering raising the awareness among local communities with the purpose of increasing people's involvement in contributing to the e-waste collection system, and thus reducing the amount of WEEE that enters the informal landfills, which is improperly handled and can affect the environment and human health. This is why the current study also considered in S2 and S3 the information process for the comparative analysis.

As far as the contribution of each process included in the system boundaries is concerned, the results illustrated in Figure 5 for the CML2001 method show that for S1, the highest percentage was attributed to the collection step (47.78%), followed by recycling (25.77%) and sorting (13.75%). The lowest values were identified for the temporary storage of the collected e-waste (0.13%), landfilling (0.65%) and transport (11.83%). The hierarchy of the process contribution to the total environmental impact of S1 was collection > recycling > sorting > transport > landfill > temporary storage. In the case of S2 (Figure 6), the highest contribution among all the involved processes was also for the collection step (32.13%). However, the obtained percentage for landfill (25.77%) was higher than that of recycling (18.20%) and transport (5.87%) in comparison with S1. The lowest value was generated in the case of the information process (0.01%). So, in the case of the results obtained for S2 using CML2001, the hierarchy was collection > landfill > recycling > transport > information. The results obtained for S3 showed a similar trend (Figure 7). The collection process (56.96%) had the highest contribution to the total environmental impact, while the lowest was identified for the sorting step (0.09%). Similar to S1, the recycling stage (18.50%) had a higher contribution than the transport (8.45%) and landfill (1.22%) processes. Thus, for S3 the identified order of the process contribution to the total generated impact was collection > recycling > temporary storage > transport > landfill > information > sorting.

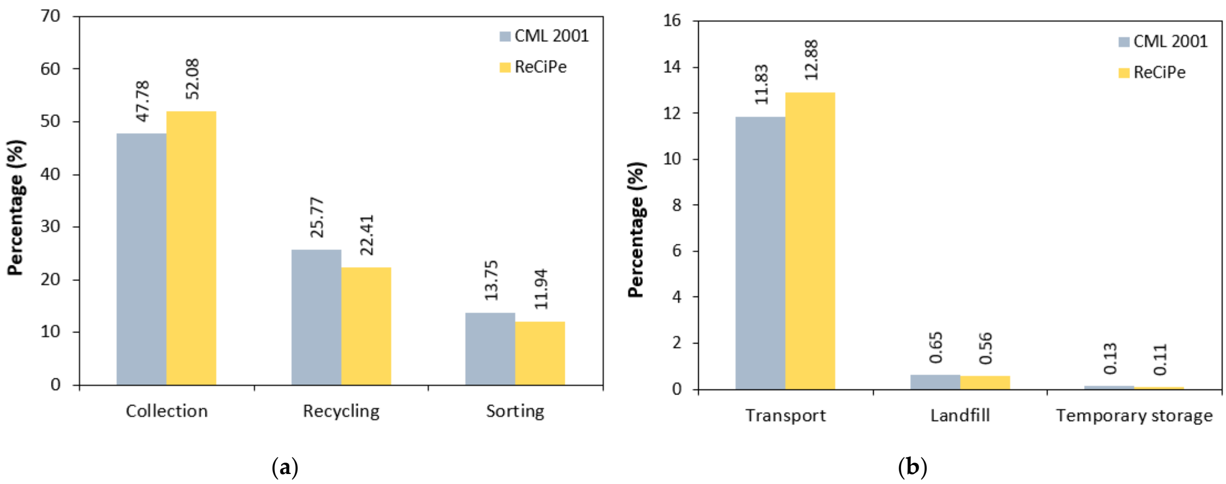


Figure 5. Process contribution to the total environmental impact of WEEE management according to S1 (CML2001 and ReCiPe methods): (**a**) Collection, Recycling, Sorting; (**b**) Transport, Landfill, Temporary storage.

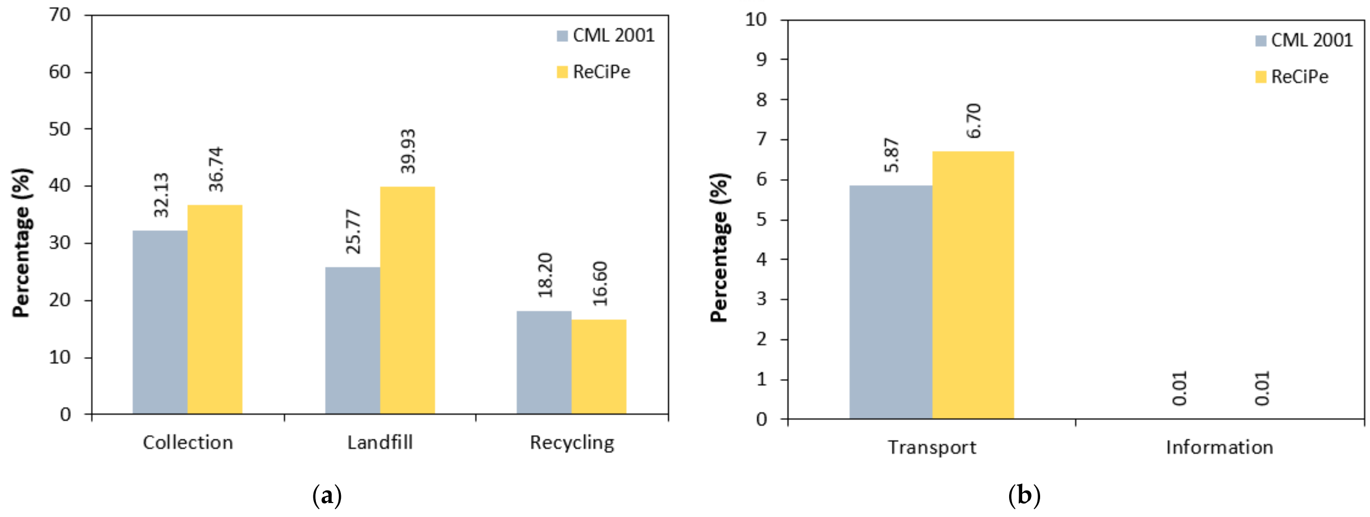


Figure 6. Process contribution to the total environmental impact of WEEE management according to S2 (CML2001 and ReCiPe methods): (**a**) Collection, Landfill, Recycling; (**b**) Transport, Information.

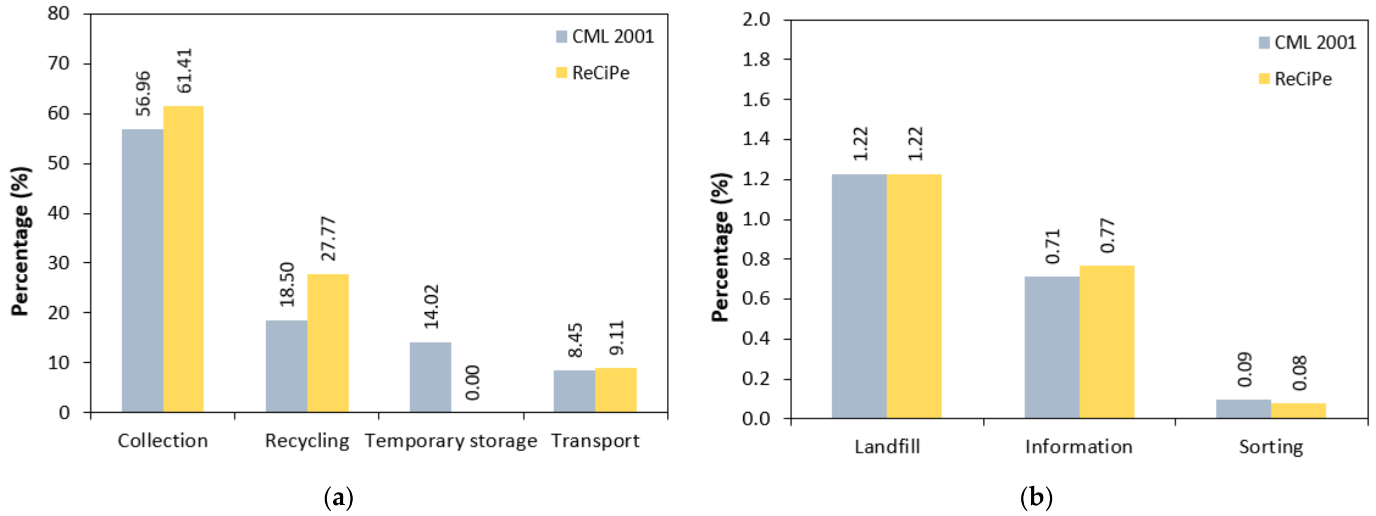


Figure 7. Process contribution to the total environmental impact of WEEE management according to S3 (CML2001 and ReCiPe methods): (**a**) Collection, Recycling, Temporary storage, Transport; (**b**) Landfill, Information, Sorting.

The results obtained by applying the ReCiPe method also showed the highest contribution to the total environmental impact of the collection step in almost all the analyzed scenarios. With a few exceptions, the hierarchy of the percentages per process was similar to the one identified when the CML2001 method was used. One difference is the fact that the highest value was obtained for the landfill stage (39.93%) for S2. Another difference is that in the case of S1, the transport process (12.88%) generated a higher contribution to the total impact in comparison with the sorting step (11.94%).

The obtained percentage contribution values for S1 through the ReCiPe method followed the hierarchy of collection > recycling > transport > sorting > landfill > temporary storage. In case of S2, the order was landfill > collection > recycling > transport > information. Finally, for S3, the hierarchy was collection > recycling > temporary storage > transport > landfill > information > sorting.

The differences between the two applied LCA methods were determined by the different characterization factors included by the methods and the fact that CML2001 is a problem-oriented methodology, while the ReCiPe method considers the cause as well as the effect [40].

To compare, a study analyzing the environmental impact of the treatment, disposal, collection and external transport of municipal waste containing various types of waste, including WEEE, found that the highest contribution to the total environmental impact was for the treatment and disposal phase (72.3%), followed by collection (18.3%) and external transport (9.4%). The research was carried out in the context of a small town in Italy with a population of 16,820 inhabitants. A functional unit of 1 ton of waste was used and the ReCiPe method was applied in order to quantify the environmental impact [20].

Results regarding the percentage contribution to the total environmental impact obtained using Impact 2002+ method in another research study showed a 75% value for the mechanical processing of WEEE in the context of a Swiss take-back and recycling system [41].

The impact category with the highest value for the applied scenarios was represented by FD (fossil depletion potential), followed by CCHh (climate changes associated with the deterioration of human health). The negative influence of these impact categories resulting from the application of the three scenarios was due to the consumption of diesel and electricity.

The LCA methodology is able to provide an overview considering the environmental aspects of different waste management practices as well as of the materials used and the emissions released into the environment. In order to analyze the contribution of the most important resources to the sustainability outcome of WEEE management as described in the Romanian case study, the percentage of electricity consumption and transportation to the total environmental impact was calculated as well, for both the CML2001 and ReCiPe methods.

The results obtained using the CML2001 method are depicted in Figure 8a. The generated data show that the highest electricity consumption was attributed to S1 (80.6%), followed by S2 (62%) and S3 (33.9%), respectively. The hierarchy for the transport contribution was the opposite though, the lowest value being identified for S1 (19.4%). For S2, the transport value was 38%, while for S3 it was 66.1%. Furthermore, it is worth comparing the energy consumption of laptop and home computer manufacturing with the total electricity consumption of their recycling. Thus, 1266 MJ are consumed for the conversion of heavy metals for laptop manufacturing, 5832 MJ are necessary for using an office laptop, while 1867 MJ of energy are estimated for the remanufacturing process [22].

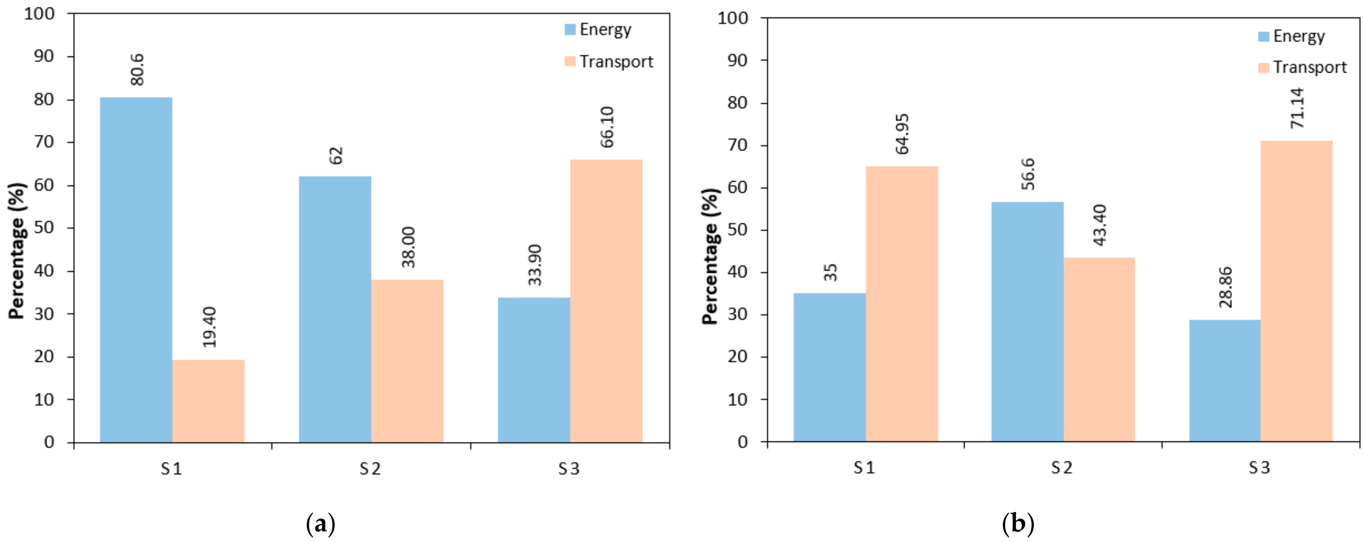


Figure 8. Electricity and transport contribution to the total environmental impact of WEEE management systems: (**a**) CML2001 method; (**b**) ReCiPe method.

The results obtained using the ReCiPe method are depicted in Figure 8b. In this case, the highest value for electricity contribution was obtained for S2 (56.6%). For S1, a percentage of 35% was identified and for S3, the lowest contribution was observed (28.86%).

As far the contribution of transport is concerned, the obtained data showed the lowest value for S2 (43.4%), while the highest was generated in the case of S3 (71.14%). For S1, the calculated percentage was 64.95%.

The proximity of recycling facilities to the collection centers, but at the same time that of the collection centers to the inhabited areas, is very important in order to reduce the environmental burden of transportation [20]. The development of strategies and policies that consider building local infrastructure in order to minimize the distance between these key points in the WEEE management system could significantly improve the impact on the environment.

Although the concepts of sustainability and a circular economy are similar in terms of the global model, interdisciplinarity, the integration of non-economic aspects and the reduction of environmental impact, the main difference lies in the fact that the circular economy exclusively involves ensuring a closed cycle of resources and secondary products obtained from the analyzed system, while sustainability entails a more extensive perspective, depending on the objectives, components and sub-processes included in the study [42]. From an environmental point of view, it is estimated that approximately 48% of emissions could be reduced through the implementation of circular economy principles [43]. Reducing the environmental impact can also thus be achieved by moving from a linear economy to a circular economy. To adapt the circular economy concept to WEEE management, actions are needed at different levels and processes within WEEE management systems. On the one hand, from the early stages, more precisely, starting with the WEEE collection process, it is important that it is carried out in the most efficient way to be able to ensure the recovery of the largest possible amount of materials that can be recycled.

The basic principles of a circular economy include the 3Rs (reduction, reuse, recycling) at the global level, and the 4Rs relative to the territory of the European Union. The 4Rs additionally include the recovery process [44]. Among these, the concept of a circular economy especially encourages reuse and remanufacturing compared to recycling, both for economic and environmental reasons. However, the reuse rate of collected WEEE is very low, 2%. In contrast, the recycling percentage of electrical and electronic waste is around 68% [45]. Thus, the technology applied for the manufacture of electrical and electronic devices represents another aspect that requires special attention in order to increase the possibility of the recovery of materials with added value, such as metals, and to decrease the concentration of toxic substances in the composition of EEE [46]. Additionally, innovation in terms of technology for the recovery of materials from the WEEE structure will allow increasing the level of inclusion of the principles of a circular economy within the management systems of this type of waste. The current available recycling methods are physical, chemical, pyrometallurgical and hydrometallurgical [47].

Although there are no environmental savings recorded through the application of LCA methodology for the analyzed scenarios, the recovery of valuable materials from e-waste contributes to the reduction in mining and industrial production activities, which can greatly harm the environment and human health. Energy savings quantified through the recovery of metals such as aluminum, copper and iron are estimated at 95%, 85% and 74%, respectively. In case of plastics, it is approximated at >80% [48]. The plastic fraction of e-waste is quite high, approximately 20–30% of the total WEEE quantities [49]. A study analyzing the WEEE management in Italy according to the five categories of e-waste established by law showed that metal, plastic and glass recycling offered the highest benefits in terms of materials recovery [39,40]. Though the collection targets are not yet fulfilled fully in Romania, the recycling rates increased from 11% in 2007 to 87% in 2014 [28]. It is thus an important aspect of the whole WEEE management system regarding sustainability [50,51]. In the e-waste management scenarios considered in the current study, several important metal and plastic parts were recovered during the recycling stage. These were considered as output data in the LCA analysis. The related data are included in Table 2.

Table 2. Recovered parts from the collected e-waste.

Recovered Part	Recovered Amount per Scenario (% of Total Recovered Parts)		
	S1	**S2**	**S3**
Aluminum scrap	2.92	3.22	3.05
Copper scrap	4.90	4.91	4.50
Iron scrap	3.81	4.12	3.89
Plastic	23.63	21.84	26.23
Steel scrap	47.95	52.73	49.86
Waste glass	16.74	13.11	12.40
Wood	0.04	0.04	0.04

Finally, to complete the perspective on our results, it should be pointed out that the performed study has several limitations. The data availability is one aspect to be considered. In Romania, there is, for example, a lack of information concerning the existence and location of WEEE collection centers, the amount of collected waste, as well as the environmental legislation attributed to e-waste management. Another issue is the fact that the available studies used different LCA methods, and more importantly, many did not normalize the obtained results in the used software in order to enable a leaner comparison between different data generated in the published research. The difficulty of including a scenario on WEEE management that encompasses the full end-of-life stage and thus can fulfill the circular economy principles is another aspect to consider. There are few recycling facilities in Romania, and even these do not carry out a full recycling process, only recovering some larger parts. Other elements such as precious metals are not put back in the cycle at this phase. Romania is not the only European country in which this occurs. Norway for example, which is one of the European territories with the best WEEE management systems, partly ensures WEEE treatment in other countries due to the limited number of facilities [16].

Furthermore, though in our study we included a wide range of types of collected WEEE, there are other components such as solar panels, batteries from electric cars and other types of WEEE that have rarely been considered together with household items, from both the personal and private sectors, and could be included in future studies to give a broader view on the overall environmental impact of a municipality. We therefore recommend the extended research of other types of WEEE, the increase in available data from collection centers and recycling facilities, a more unified approach to applying LCA and related software, as well as the inclusion of raising awareness among the population phase in the study of WEEE management across different countries and regions around the world. Since the full recycling or recovery of valuable materials from WEEE can take place in a different territory than the one for collection and treatment, and given the issues related to the developing world, cross-country collaborations are key for more efficient research and the innovation of WEEE management in the context of a circular economy and a more sustainable future. The main aspects that should be tackled to address the global WEEE issue and implement efficient management systems are preventing or minimizing WEEE generation in order to reduce the e-waste streams, innovating recycling technology as well as the manufacturing processes in order to improve resource recovery, raising awareness among the population, optimizing WEEE treatment, reducing energy consumption, and the efficient implementation of all established roles and processes that are part of a WEEE management system.

4. Conclusions

The current study aimed to analyze the sustainability of WEEE management in the Municipality of Iasi, Romania through three different scenarios implemented in the period 2018–2019. The research analysis was carried out by applying a standardized LCA methodology, in GaBi Education software, through the application of two methods, CML2001 and ReCiPe. One innovative aspect of the performed analysis was the inclusion in the system boundaries of raising awareness among the local community. There are a few limitations that were acknowledged in the current study, such as the lack of data from collection centers and the difficulty in comparing the calculated environmental impact with other studies due to the different ways of applying the methodology and processing the generated results. The results showed that this process has a low environmental impact among all the included processes. The highest contribution to the total obtained impact was that of the collection stage in all three scenarios, this showing that the environmental burden could be reduced through the implementation of sustainable transport routes for gathering all the e-waste. In terms of impact categories, the highest value was determined through the CML2001 method for the marine aquatic ecotoxicity potential (MAETP) impact category in S2 and for the abiotic depletion fossil (ADPf) impact category in the cases of S1 and S3. By comparison, the ReCiPe method results showed a lower value for ozone depletion (ODP) and a higher one for fossil depletion (FD) for all three scenarios, which indicates that a reduction in fossil fuel consumption is required.

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