ENVIRONMENTAL ASSESSMENT OF THE RECOVERY OF PRINTED CIRCUIT BOARDS IN GREECE

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Abstract
The volume of waste electrical and electronic equipment (WEEE) is growing three times faster than the average municipal waste stream in the European Union. According to the European Commission the amount of WEEE produced per EU citizen is about 17-20 kilograms per year and is expected to grow annually between 2.5% and 2.7%.

On the other hand, there is increasing concern over the security of supply of a wide range of strategic or critical raw materials many of which are speciality metals which are essential to the functioning of electronic equipment, albeit used in small concentrations within a few of the components. These materials include the precious metals, gold, silver and platinum and metals such as copper, as well as the Rare Earth Metals. One approach to improving the supply of these materials is to recover as much as possible from the WEEE that is currently processed under the WEEE Directives, which were designed primarily to prevent this waste stream going to landfill.

Printed circuit boards (PCBs) are the most valuable component of WEEE, containing a lot of critical metals. Practically all electronic devices contain PCBs. The annual collection of PCBs is estimated to be 1.5-2 million tonnes, which corresponds to 3%wt of the total WEEE collected in Europe. The aim of this study is to quantify the environmental benefits from recovering PCBs in Greece in 2016. The functional unit is defined as "the annual collection of PCBs in Greece for 2016". The results indicate that the recovery of PCBs has a positive environmental impact in each and every of the impact categories assessed.

Keywords: WEEE, recovery, critical metals, LCA, Printed circuit boards

INTRODUCTION

A PCB or Printed Wiring Board is a board that mechanically supports and electrically connects electronic components through conductive pathways manufactured onto a non-conductive substrate. It forms part of a larger electronic product. The printed circuit board (PCB) is defined as a structural product produced from transferring electrical circuit design through printing or image transfer technology to the surface or interior of an insulating material. During the subsequent processing, integrated circuits, transistors, diodes, passive components (e.g., resistors, capacitors, connectors) and other electronic components may be added onto the PCB. PCB can serve as a platform for linking various electronic components through wire connections and enabling the integration of electrical signals and function performance.

PCBs are the most valuable component of WEEE. Practically all electronic devices contain PCBs [1]. The annual collection of PCBs is estimated to be 1.5-2 million tonnes, which corresponds to 3%wt of the total WEEE collected [2, 3]. PCBs can contain more than ten times the concentration of precious metals, compared to the respective metal ores [1]. Due to their high metal content (approx. 40% wt.), PCBs are an attractive source for secondary materials in addition to an environmental threat due to the presence of dangerous materials such as cadmium, mercury, lead, and brominated flame retardants [4]. The sustainable management of this waste stream is thus important to prevent the loss of these materials and to mitigate the growing shortage of resources [4].

LCA IN WEEE MANAGEMENT

LCA is widely used for WEEE management [5]. For instance, Hischier et al. studied the environmental impacts of the Swiss take-back and recycling systems for e-waste [6]. The results showed that the e-waste recycling system and take-back were clearly advantageous from an environmental perspective, compared to incineration. The same group of authors recalculated the impacts of their scenarios 5 years later. In comparison between the environmental impacts of the WEEE recovery scenarios 2009 and 2004, both calculated with ecoinvent v2.01 data, shows that the impacts per t of WEEE in 2009 were slightly lower. This appears to be mainly due to the changes in the treatment of plastics (more recycling, less incineration) [7]. The same authors argue that plastics play an increasingly important role in reaching the recovery and recycling rates defined in the European WEEE Directive. The results of their LCAs, which were extensively tested with sensitivity analyses, show that plastics recycling is clearly superior to the alternatives considered in their study (i.e. municipal solid waste incineration and virgin plastics production) [8]. Recently, Hong et al. found that E-waste recycling with an end-of-life disposal scenario is environmentally beneficial because of the low environmental burden generated from human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity categories. Landfill and incineration technologies have a lower and higher environmental burden than the e-waste recycling with an end-life disposal scenario, respectively [9]. LCA is used as the “tool” to assess the climate co-benefits from WEEE recycling in Japan. Life cycle GHG emissions were estimated from the overall recycling process of major home appliances in Fukuoka Prefecture under Japan’s home appliances recycling law. The calculation indicates that by implementing an appropriate WEEE recycling and resource recovery program, a significant amount of GHG emissions could be avoided that would have otherwise occurred through the virgin production of materials [10].

Literature review reveals that there are also a few studies focusing on the environmental impacts of waste resulting from PCBs. For instance, the goal of the study by Xue et al. [11] was to quantitatively assess the environmental impact of the processes in a formal PCB recycling chain. LCA was applied to a formal recycling chain that includes the steps from waste liberation through materials refining. The metal leaching in the refining stage was identified as a critical process, posing most of the environmental impact in the recycling chain. Global warming potential was the most significant environmental impact category after normalization and weighting, followed by fossil abiotic depletion potential, and marine aquatic eco-toxicity potential. Scenario modelling results showed that variations in the power source and chemical reagents consumption had the greatest influence on the environmental performance. Optimizing the collection mode, increasing the precious metals recovery efficiency in the beneficiation stage and decreasing the chemical reagents consumption in the refining stage by effective materials liberation and separation are proposed as potential improvement strategies to make the recycling chain more environmentally friendly [11].

The goal of the next study by Rubin et al. [12] was to evaluate and compare two processes for recovering copper from PCB scrap via means of LCA. Initially, a review was conducted, focusing on material recovery processes adopted as EoL options for WEEE management; several methods for copper recovery from PCB scrap were found. LCA methodology was then applied in order to evaluate and compare two of these processes: mechanical and electrochemical. Evaluation of the impact categories considered in the study has shown that the process that uses acquaregia has better environmental performance. The work reported here can be seen as a starting point for more in-depth evaluations of these and other material recovery processes, especially in countries such as Brazil, where WEEE management is often neglected in the absence of a well-structured recycling chain, it is usually disposed of in landfills [12].

Finally, the goal of the study by Fogarasi et al. [2] was the quantitative evaluation of the environmental impact of two original electrochemical processes for recovering copper from waste PCBs. Both electrochemical processes involve the dissolution of copper from PCBs with its simultaneous electroextraction from the resulting leaching solutions. The first process uses direct electrochemical oxidation while the second one achieves the dissolution of copper through mediated electrochemical oxidation using the Fe3þ/Fe2þ redox couple. The Biwere Heinzle method is applied to determine the environmental impact of the processes in the established optimum conditions. The values of the General Environmental Indices, calculated for the inputs and for the outputs, are quite small, close to the minimum possible, indicating that both electrochemical processes have a very low environmental impact [2].

RESULTS AND DISCUSSION

In the case of reuse, the environmental benefits from WEEE diversion programs are drawn from the associated benefits of reuse, which include the avoided environmental impacts of recycling (collection, processing, hauling), the avoided environmental impacts of raw material acquisition and manufacturing, attained when recyclables are used instead of virgin resources, as well as the avoided impact of waste disposal (landfill). Reuse of electrical and electronic equipment diminishes most or all of the inputs needed to manufacture the replacement product from virgin materials. Avoiding these “upstream” processes significantly reduces energy usage, associated greenhouse gas emissions, and other pollutant emissions as well.

Because of the complex composition of electronic appliances, WEEE diversion strategies, such as reuse and preparation for reuse, have a twofold purpose. WEEE must be seen as a dangerous waste stream, which, if not treated properly, can cause severe environmental and human health damage [13]. On the other hand, the numerous materials that constitute WEEE are an enormous resource potential. In order to demonstrate the potential for diverting appliances from WEEE via reuse or preparing for reuse, the case study of printed circuit boards (PCBs) is selected.

The case of PCBs in Greece's WEEE in 2016

In order to demonstrate the environmental gain resulting from WEEE reuse, the case study of the PCBs was selected because practically all electronic devices contain PCBs. Data on the recovery of PCBs for 2016 in Greece were collected from Appliances Recycling S.A. Based on the data submitted by Appliances Recycling S.A., the collection of WEEE in Greece is rising steadily. Specifically, the collection was 44,000 tn in 2014, 48,000 tn in 2015, while for 2016 it is estimated at 52,000 tn. For 2016, the breakdown of WEEE recovery is presented in Table 1.

Table 1. WEEE fractions recovered in Greece for 2016.

Recycled fraction	**%**	**Quantity (tonnes)**
Ferrous metals	50.47	26,244.4
Non-ferrous metals	3.05	1,586.0
Plastics	10.73	5,579.6
Glass	9.34	4,856.8
Electromechanical parts	7.71	4,009.2
Other recoverable material	3.42	1,778.4
Non recoverable material	11.91	6,193.2
Total	**100**	**52,000.0**

These data were then modeled in SimaPro 5.1. Based on the data provided by appliance Recycling S.A., PCBs in Greece constitute 1.69% of the 52,000 tn of WEEE collected, i.e. 878.8 tn of PCBs were collected in Greece in 2016. This value corresponds to PCBs greater than 10 cm^2 in area, i.e. PCBs resulting from desktop computers.

Based on the aforementioned data and the engagement of the SimaPro 5.1 database, a first attempt will be made in order to quantify the environmental benefits from collecting 878.8 tn of PCBs in Greece in 2016. The functional unit is defined as "the annual collection of PCBs in Greece for 2016". The PCBs were modeled as avoided "printed board I" from the SimaPro 5.1 database. The life cycle impact assessment results per impact category are presented in Table 2. Moreover, the normalised impact assessment results are presented in Figure 1.

Table 2. Life cycle impact assessment results for the recovery of 1 kg of PCBs in Greece in 2016.

Impact category	Unit	Printed board I
abiotic depletion	kg Sb eq	-1.05
global warming (GWP100)	kg CO_2 eq	-145
ozone layer depletion	kg CFC-11 eq	-0.00000586
human toxicity	kg 1,4-DB eq	-37.1
fresh water aquatic ecotox.	kg 1,4-DB eq	-89
marine aquatic ecotoxicity	kg 1,4-DB eq	-84300
terrestrial ecotoxicity	kg 1,4-DB eq	-0.16
photochemical oxidation	kg C_2H_2	-0.177
acidification	kg SO_2 eq	-4.29
eutrophication	kg PO_4^{---} eq	-0.0312

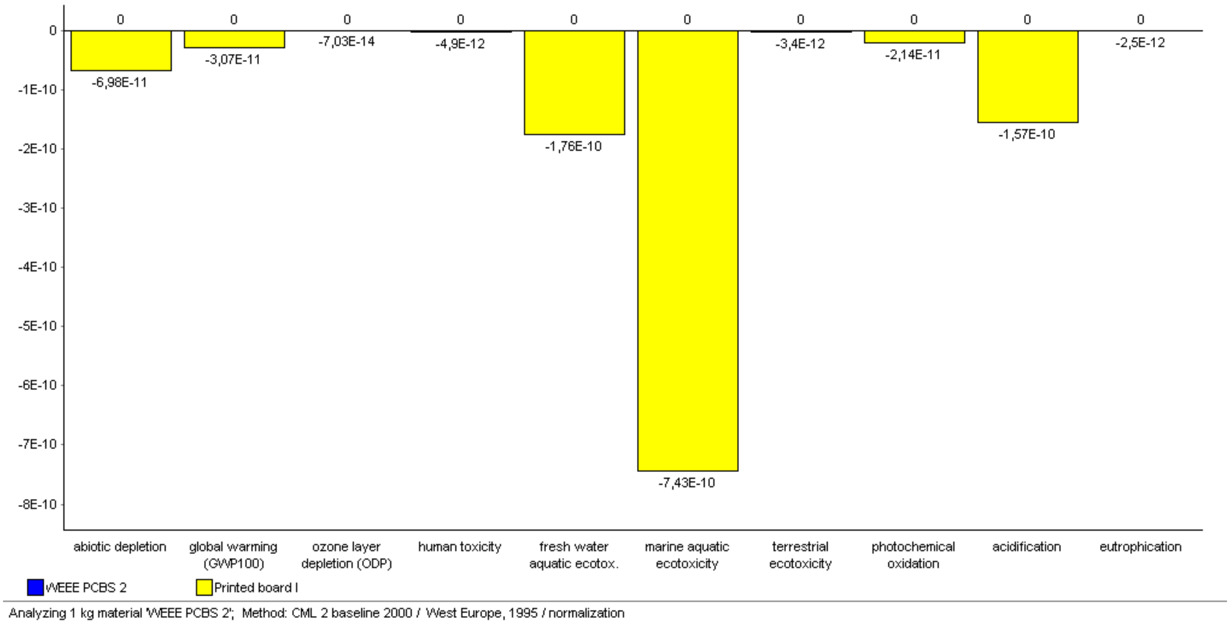

Figure 1. Normalised environmental impacts from the production of 1 kg of PCBs.

As expected, the recovery of PCBs has a positive environmental impact in each and every of the impact categories, indicated by the negative values in Table 2. Moreover, the normalised impact assessment results indicate that the impact categories mostly affected by the recovery of PCBs are the marine aquatic ecotoxicity, the freshwater aquatic ecotoxicity, the acidification and the depletion of abiotic resources (see Figure 2).

CONCLUSIONS

Printed circuit boards (PCBs) are the most valuable component of WEEE, containing a lot of critical metals. Recovery of valuable constituents of PCBs is very attractive since practically all electronic devices contain PCBs. In order to demonstrate the environmental potential for diverting appliances from WEEE via reuse or preparing for reuse, the case study of printed circuit boards (PCBs) has been presented in the present paper via means of LCA. As expected, the recovery of PCBs has a positive environmental impact in each and every one of the impact categories examined.

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