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A profitability assessment of European recycling processes treating printed circuit boards from waste electrical and electronic equipments

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ABSTRACT

The management of waste electrical and electronic equipment (WEEE) is a well-stressed topic in the scientific literature. However, (i) the amount of cash flows potentially reachable, (ii) the future profitability trends and (iii) the reference mix of treated volumes guaranteeing a certain profitability level are not so clear, and related data are unrecoverable. The purpose of the paper is to fill in this gap by identifying the presence of profitability within the recovery process of waste printed circuit boards (WPCBs) embedded in WEEE. Net present value (NPV) and discounted payback time (DPBT) are used as reference indexes for the evaluation of investments. In addition, a sensitivity analysis of critical variables (plant saturation level, materials content, materials market prices, materials final purity level and WPCBs purchasing and opportunity costs) demonstrates the robustness of the results. Furthermore, the calculation of the national NPV for each of the twenty-eight European nations (in function of both WPCB mix and generated volumes) and the matching of predicted WPCB volumes (within the 2015–2030 period) and NPV quantify potential advantages. The break even point of gold allowing some profits from selected recovery plants goes from 73 to 93 ppm per WPCB ton, for mobile and field plants, respectively. Finally, the overall European values go from 2404 million € (mobile plant) to 4795 million € (field plant) in 2013, with Germany and United Kingdom as reference nations.

Contents

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1. Introduction

The mass electronics sector is one of the most important sources of waste, both in terms of volume [1] and materials content [2], with dangerous effects on the environment [3,4]. Even if great improvements in the e-waste recovery (with relevant increases from the sustainability point of view) were done in comparison with decades ago, both current recovery performance and recyclability measurement procedures [5] are yet inadequate to counteract the annual increase of generated waste, especially considering WPCBs, or the most complex, hazardous, and valuable component of e-waste [6–8]. Shortfalls also emerge from the point of view of optimization techniques that, even if well explained in the literature and applied in several fields [9,10], are not so common within the EoL context. Consequently, the definition of the goal function [11], the integration of several control parameters [12], the implementation of dedicated simulation models [13] and the application of sensitivity analyses [14] for the definition of future trends [15] are relevant topics scarcely debated by the experts, with a negative impact on the definition of innovative – and more sustainable – end-of-life (EoL) strategies [16–18]. In contrast, basic guidelines for the reuse, recovery and recycling of WEEE were established all over the world in the last decades, and many authors analysed and compared different WEEE directives and national recovery systems [19–23]. However, all these analyses were rarely implemented [24,25]. In particular:

- WEEE volumes are clearly increasing and the experts already assessed their economic potential. However, they considered entire e-waste, and not only printed circuit boards (PCBs) [26];
- Interesting economic models were already tested in different industrial contexts (e.g. the automotive sector), but not in the mass electronics industry [27].

Addressing these gaps, the aim of this paper is multi-fold. First, the potential profitability characterizing all the phases of a typical PCB recovery process focused on four WEEE categories (big household appliances, small household appliances, IT and telecommunication equipments and consumer equipments) and different plant configurations (field and mobile ones) are assessed. Second, the economic profitability is defined for nine products (refrigerators, washing machines, air conditioners, desktop PCs, notebook PCs, mobile phones, CRT TVs, stereo systems, digital cameras) pertaining to three of the previous four categories (given the lack of literature data, small household appliances are not considered). Third, the break even point is set on the gold content of WPCBs, for both field and mobile plants. Fourth, potential profits are compared with different mixes of WPCBs treated by multi-core plants. Fifth, the overall profit of WPCB recycling plants is estimated for each European nation. Finally, future profitability trends are defined for Europe as a whole. These results could assist governmental and industrial actors in defining corrective measures on current directives.

The paper is organized as follows:

- Section 2 presents the research framework and a description of the economic model considered within this work;
- Section 3 describes the results coming from its application within the European WEEE market;
- Section 4 presents a sensitivity analysis on a set of critical variables;
- Section 5 conduces an overall discussion of the results and an estimation of future trends;
- Section 6 presents some concluding remarks and future perspectives.

2. Research framework

PCBs are the most valuable component embedded into Electrical and Electronic Equipments (EEEs). The current amount of electronic systems is impressive. Only considering that, on average, a PCB accounts almost from 3% to 5% of the overall weight of a WEEE, the expected volumes of WPCBs are enormous and accountable in several million tons [28,29]. However, current WEEE directives (applying weigh-based principles) seem to do not adequately take into account their management [8,30].

2.1. European WEEE volumes

The entire work starts from the overall amount of WEEE collected in the EU-28 during 2013 [31]. This year is selected as reference because the most recent data referring to all of the EU-28 nations pertain to 2013. These data are divided into categories (Cat) following the WEEE classification guideline defined within the European WEEE Directive. Among them, only four are selected because of their relevance (about 94%) on the overall amount of WEEE volumes. Following this classification (Cat1, Cat2, Cat3 and Cat4): Cat1 WEEE represents big household appliances (e.g. fridges, washing machines, air conditioners, etc.); Cat2 WEEE represents small household appliances (e.g. vacuum cleaners, toasters, fryers, etc.); Cat3 WEEE represents IT and telecommunication equipments (e.g. PCs, tablets, notebooks, smartphones, etc.) and Cat4 WEEE represents consumer equipments (e.g. TVs, stereo systems, digital cameras, etc.). Given these WEEE categories, it is possible to classify the type of PCB embedded into these products [32]. In fact, Cat1 and Cat2 WEEE are known to embed low grade PCBs. In contrast, Cat3 and Cat4 WEEE generally embed medium-high grade PCBs. Table 1 reports data about WEEE annual collected volumes in EU-28 for each of the four selected categories.

2.2. PCB recycling processes

A generic PCB recycling process can be seen as the sum of three main phases that, starting from PCBs, are able to obtain as final output a set of (almost pure) raw materials. These phases can be distinguished in: disassembly, treatment and refining [28]. During disassembly, hazardous components (e.g. condensers or batteries) and valuable ones (e.g. memories and microprocessors) are disassembled from the main board and destined to specific treatment processes. During treatment, PCBs are crushed into micro pieces up to become a uniform powder, through the use of several technologies (e.g. shredders and grinders). Subsequently, these powders are separated between metal and non-metal ones by exploiting their different physical principles (e.g. density, magnetism or weight). Finally, metal powders are refined through the available technologies (e.g. pyrometallurgy, hydrometallurgy or a mix of them), up to obtain almost pure secondary resources [24,33]. Considering this paper, the refining process taken into account is the hydrometallurgical methodology. However, the