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Automotive printed circuit boards recycling: an economic analysis

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ABSTRACT

End of Life Vehicles (ELVs), together with Waste from Electric and Electronic Equipments (WEEEs), are re-known as an important source of secondary raw materials. Since many years, their recovery allowed the restoring of great amounts of metals for new cars' production. However, the management of electronic systems embedded into ELVs is yet rarely considered by the scientific literature. The purpose of the paper is trying to fill in this gap through the proposition of an innovative economic model able to identify the presence of profitability within the recovery process of automotive Waste Printed Circuit Boards (WPCBs). Net Present Value (NPV) and Discounted Payback Time (DPBT) will be used to demonstrate the validity of investments in this type of plants. Furthermore, a sensitivity analysis on a set of critical variables (plant saturation level, gold (Au) content, Au market price, Au final purity level, WPCBs purchasing cost and opportunity cost) will be conducted for the evaluation of the impact of significant variations on results. Finally, the matching of predicted European ELVs volumes (during the period 2015–2030) and NPVs coming from the economic model will quantify the potential advantages coming from the implementation of this new kind of circular economy.

1. Introduction

In the past twenty years, the booming consumer electronics industry rapidly changed the economic and social landscape (Li et al., 2015; Golembiewski et al., 2015; Sun et al., 2015). Highly innovative products, with even lower lifetimes, generated a so high amount of obsolete electronic devices that they became increasingly a global challenge, nowadays re-known as WEEEs, or electronic wastes (e-wastes) problem (Lu et al., 2015; Hong et al., 2015). Printed circuit boards (PCBs) represent the most complex, hazardous, and valuable component of e-wastes. They can contain more than 60 elements (on average), including plenty of heavy metals (such as Lead (Pb), Chromium (Cr), Cadmium (Cd), Mercury (Hg), Arsenic (As)) and toxic organic substances (such as brominated flame retardants, polycyclic aromatic hydrocarbons, dechlorane plus, etc.) (Song and Li, 2014; Huang et al., 2014). From the automotive sector point of view, the use of PCBs inside a car for the management of almost all the functionalities of a vehicle drastically increased in the last decades (Kim et al., 2014). Hence, this trend undoubtedly contributed in increasing volumes of PCBs produced and, so, to the overall amounts of WPCBs dismantled. In fact, the automotive sector, together with the mass electronics sector, is one of the most important sources of waste, both in volumes (Zorpas and Inglezakis, 2012; Cucchiella et al., 2014a; S-iYoshida et al., 2014; Tian and Chen, 2014) and in materials content terms (Berzi et al., 2013; Uan et al., 2007). For this reason, basic guidelines for the reuse, recovery and recycling of ELVs were established all over the world in the last decades. Within the scientific literature, lots of papers analysed and compared different ELV directives and national recovery systems (S-iYoshida et al., 2014; Zhao and Chen, 2011). However, some topics were only superficially studied, for example:

- The recycling of scrap automotive electronics (e.g. Electronic Control Units (ECUs)), together with its environmental impacts, does not appears to have been adequately assessed by the experts (Wang and Chen, 2013a, 2012);
- Some authors identified the potential support in the development of new circular economies given by the recovery of automotive electronic systems, but no practical applications are available in literature (Cucchiella et al., 2015a);
- The existing economic models assessing the profitability of recycling plants are very few, and specialized on a particular phase of the process (Ghosh et al., 2015);
- The limited technological development of scrap automotive electronics processes was assessed by some authors as one of

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the main reason for the lacking of literature focused on this topic. This way, the implementation of new kinds of plants (e.g. mobile recycling plants) was not taken into account since now (Zeng et al., 2015).

Given that, the aim of this paper is threefold. From one side, there is the need to define a mathematical model able to assess the potential profitability characterizing all the phases of a typical WPCBs recovery process (or dismantling, pretreatment and refining). From a second side, this calculation has to be done on different types of plants (for example, field and mobile ones). Finally, the potential profitability has to be linked with the available previsions on future ELVs generated volumes for the quantification of the expected market dimension. The important findings of this investigation could be very helpful to governmental and industrial actors for a direct comparison with results coming from similar types of models available in literature, so to better understand the lost opportunity, by trying to define corrective measures for the management of these new types of e-wastes.

The paper is organized as follows: Section 2 presents a description of the research framework and. Section 3 presents theoretical methods adopted within this study and the economic model at the base of the overall analysis. Economic results are presented in Section 4, under the form of NPV and DPBT indexes. Additionally, a sensitivity analysis on the main critical variables (Section 5) and an overall discussion of results (Section 6) will be conducted. Section 7 presents concluding remarks and future perspectives.

2. Research framework

ECUs are among the most valuable electronic devices embedded in modern vehicles. They are able to perform the reading of signals coming from sensors embedded in a car, and control the behaviour of many sub-systems, as engine, air conditioning system, infotainment system, safety devices, etc. (National Instruments, 2009). The current amount of electronic systems is impressive, both in numbers and in impact on costs. In fact, a modern medium-sized car can embed up to 15 electronic systems on average (Kripli et al., 2010; Freiberger et al., 2012) and luxury cars can reach up to 50 among microcomputers and electronic components (Wang and Chen, 2011). Furthermore, a statistic of the Bayerische Motoren Werke Corporation shows that, generally, these systems can account for more than 30% of total vehicle cost, reaching more than 50% in luxury cars (Wang and Chen, 2013b). These last data alone allow to evidence how much important is the recovery of the embedded value in these components. However, current ELV directives (based on weighting principles) seems to do not adequately take into account the management of these types of e-wastes (Cucchiella et al., 2015a). Hence, there are no benefits for the actors involved in the automotive reverse logistic chain to invest in dedicated recovery centres (Cucchiella et al., 2015b).

2.1. Automotive PCBs characterization

Before the treatment of any kind of WPCBs amounts, there is a materials' characterization phase. This means a definition of the set of materials embedded in a certain amount of WPCBs, by chemically analysing a sample of them. This is a relevant phase because it allows to: (i) comprehend the presence (or not) of valuable materials (this way a WPCB is classified as high, medium or low grade waste), and (ii) define the expected revenues coming from their recovery. In literature, the common ways to characterize WPCBs are essentially two: (i) considering already available data coming from other papers or intra-governmental reports (UNEP, 2013), and (ii) implementing dedicated laboratory tests (Wang and Gaustad, 2012). The first one is the most common in papers focused on the economic sustainability of PCBs recycling processes. The second one is common when environmental sustainability is the main focus. Given both the clear focus of this paper on the economic side of sustainability, and the lack of existing data about automotive PCBs composition, the approach selected by the authors was the exploitation of existing data coming from industrial database. This explains the decision to consider IMDS as a relevant source of data from which starting with the economic assessment. IMDS is a materials data management system used in the automotive sector. Designed by Audi, BMW, Daimler, HP, Ford, Opel, Porsche, VW, and Volvo, IMDS was then adopted by other car manufacturers, so becoming a global standard used by almost all the automotive Original Equipment Manufacturers (OEMs) worldwide. Data related to 500 different automotive electronic devices were extracted and, subsequently, categorized into four typologies basing on their weights distribution (divided into quartiles). The four resulting groups are represented by:

- Small WPCBs, going from 0.2 g up to 8.7 g;
- Medium-small WPCBs, going from 8.8 g up to 52.9 g;
- Medium-big WPCBs, going from 53.0 g up to 134.2 g;
- Big WPCBs, going from 134.3 g up to 477.9 g.

This choice was purely objective and derives from the fact that waste automotive PCBs are very different in terms of size, shape and composition, depending on their functionality (Wang and Chen, 2013a). Hence, a subdivision like the one commonly done for WPCBs coming from WEEEs (or high, medium and low grade waste) was considered as not representative.

2.2. WPCBs recycling processes

Starting from the main assumption that scrap automotive electronic devices are, in effect, WPCBs, consequently it is possible to consider the same technological process followed for the recycling of WPCBs coming from WEEEs (Wang and Chen, 2013a, 2012; Cucchiella et al., 2015a). Hence, the recycling process can be seen as the sum of three main phases that, starting from WPCBs, are able to obtain as final output a set of (almost pure) raw materials. These phases can be distinguished in: dismantling, pretreatment and refining (Sohaili et al., 2012; Yu et al., 2009) – see Fig. 1.

During disassembly, both the casings embedding PCBs and toxic components present on the main board are separated. Toxic components (e.g. condensers or batteries) are disassembled and destined to specific treatments for hazardous materials. Instead, casings (generally, Aluminium (Al)-made elements) can be directly sold to smelters, becoming an additional source of revenues for recyclers. The pretreatment process is implemented through a series of dedicated machines, or shredders, grinders and separators (based on several physical principles). During pretreatment, WPCBs are crushed into micro pieces up to become a uniform powder, through the use of shredders and grinders. After this phase, powders are separated basing on their composition, by distinguishing metal from non-metal powders (Zeng et al., 2015; Li and Xu, 2010). Nowadays, these last ones are destined to landfills, however there are interesting works studying alternative (and valuable) ways to reuse them for different purposes (Li et al., 2012; Hadi et al., 2013). Finally, metal powders are refined, up to obtain almost pure secondary resources (the purity level differs from on material to another (Wang and Gaustad, 2012)) directly reusable for the production of new goods. The refining process can be based on different technologies (e.g. pyrolysis, pyrometallurgy, hydrometallurgy, biometallurgy). In this work, hydrometallurgy is considered