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Corresponding Author: Mr. Paolo Rosa,

Corresponding Author's Institution: Politecnico di Milano

First Author: Paolo Rosa

Order of Authors: Paolo Rosa; Sergio Terzi

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Waste Electrical and Electronic Equipments versus End of Life Vehicles: a state of the art analysis and quantification of potential profits

Paolo Rosa[a,*] and Sergio Terzi[a]

Politecnico di Milano, Department of Management, Economics and Industrial Engineering
Piazza Leonardo Da Vinci 32, 20133 Milano - Italy

* Corresponding author. Tel.: +39-02-2399-9537; fax: +39-02-2399-2730. *E-mail address:* paolo1.rosa@polimi.it

Abstract

Waste Electrical and Electronic Equipments (WEEEs) and End of Life Vehicles (ELVs) are two of the main waste streams, after municipal solid wastes, both in volumes and growth rates terms. Even if their management begins to be adequately regulated almost worldwide, there are still clear lacks to be solved in many aspects. The aim of this paper is the comparison, through a structured literature analysis, of these waste streams under several perspectives, by evidencing current differences and potential commonalities. In addition, a quantification of potential profits rising from a joined management of different sources of PCBs is described in the last part of the paper.
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1. Introduction

End of Life Vehicles (ELVs), together with Waste Electrical and Electronic Equipments (WEEEs), are two of the main sources of secondary raw materials. Yearly, impressive amounts of wastes, quantified in several million tons by different experts and organizations (e.g. [1, 2]), are generated worldwide. Given the continuous increase of these volumes, during the last decades many international directives were introduced, trying to regulate flows of materials both landfilled and illegally shipped abroad. However, the adopted approaches favoured the only recovery of basic materials.

Nomenclature

ASR Automotive Shredder Residue
ELV End of Life Vehicle
EoL End of Life
PCB Printed Circuit Board
WEEE Waste Electrical and Electronic Equipment

This way, many critical issues (a short list of them is reported here) raised during the years:

- A continuous landfilling of valuable resources;
- A common use of non-sustainable design procedures during the product development process;
- An absence of political support on investments in new recovery plants;
- A low performance level reached by current recycling technologies;
- A strong disaggregation of reverse logistic chains;
- A current focus on basic materials recovery;
- An absence of best practices and innovative business models.

The aim of this paper is the comparison, through a structured literature analysis, of WEEE and ELV waste streams under several perspectives, by evidencing current differences and potential commonalities. In addition, a quantification of potential profits rising from a joined management of PCBs from different waste streams is described in the last part of the paper.

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The paper is organized as follows: Section 2 presents a series of distinguishing points about the current management of WEEEs and ELVs. Section 3 assesses existing commonalities of these two waste streams. A quantification of potential profits and a discussion of results is conducted in Section 4. Section 5 presents some concluding remarks and future perspectives.

2. WEEEs versus ELVs - distinguishing points

WEEEs and ELVs are the two main sources of waste. However, their evolution followed different paths. The recycling of ELVs is a process existing since the ‘60s, and the reuse of scrap metals is not a new idea. Instead, the recycling of WEEEs is a modern process, developed since the ‘90s. Even if technologies applied in these two processes are similar (at least at macro level) their evolution brought to different focuses and performances. The management of waste PCBs is an important example going into this direction.

From the WEEE side [3, 4], consumer and industrial wastes are collected by formal actors (public or private collection points) and directly transferred to authorized treatment facilities. Here, depending on the type of WEEE, these are disassembled up to divide valuable components and hazardous elements. Both valuable and hazardous components are stored and, then, transferred to dedicated recycling plants. The remaining WEEE mass is directly shredded and separated onsite up to recover basic materials (e.g. construction metals, plastics, wood, glass, concrete, etc.) – see Figure 1. Being PCBs one of the most valuable components, they are separated from the wasted product during disassembly, classified, stored and transferred to dedicated plants for the final recovery of precious metals.

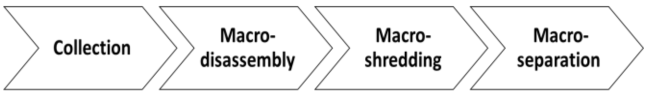

Figure 1. A typical WEEE recycling process – Adapted from [3]

From the ELVs side, cars can be distinguished into two main groups, premature and natural ELVs. Premature ELVs are cars that reached their End of Life phase because of a big accident. Instead, natural ELVs are cars reaching the End of their Life because of obsolescence. Whatever the ELV type, they are collected in many different ways (e.g. official dealers, body shops, auto wreckers, etc.). Then, they are deleted from the public register and depolluted from the main pollutant and hazardous components (e.g. batteries, fuel, oils, filters, etc.). Subsequently, most valuable parts (e.g. engines, catalysts, radiators, gearboxes, etc.) - if functioning - are disassembled and reused as spare parts in the secondary market. The car hulk is, then, crushed and fragmented into little scraps. At the end, these scraps are separated by exploiting their physical characteristics (e.g. density, weight, magnetism, etc.) up to obtain a uniform amount of materials. In general, the metal part is directly reintroduced in the automotive supply chain (as input material for foundries). Instead, the non-metal part (generally named Auto Shredder Residue - ASR) is currently landfilled or used as fuel for energy generation purposes [5] – see Figure 2. Information about non-reusable automotive PCBs are rare to find in literature. However (with a good approximation), it is possible to say that, if not disassembled from the car, automotive PCBs are crushed together with car hulks [6]. An important distinction between WEEEs and ELVs is present also in terms of strategies followed during the end of their life. In fact, recycling is the preferred strategy for the management of WEEE components [1] and remanufacturing the most common one for ELV components [7]. Undoubtedly, this distinction relates to the intrinsic value of cores. In fact, components embedded into WEEEs are, generally, low / medium value elements and their remanufacturing would not allow to re-enter from sustained costs. As opposite, automotive components (especially the mechatronic ones) have a very high value (because of their complexity) and the demand coming from the secondary market is well-developed. This way, remanufacturing costs are completely covered by revenues, so guaranteeing good profits to the actors involved in these activities. A reference market for remanufactured parts is in the USA.

Figure 2. A typical ELV recycling process – Adapted from [5]

Figure 3. A typical PCB recycling process – Adapted from [13]

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The illegal shipment of great amounts of scrap products abroad is another issue characterizing both WEEEs and ELVs. However, volumes and final destinations are very different. From the WEEE point of view, illegal flows reach approximately 50% of volumes generated yearly in the world. This means that, by considering a global annual amount going from 30 to 50 million tons of WEEEs [1], illegal shipments reach approximately 15-25 million tons. Furthermore, their destinations are well-known by the experts, and represented by several developing countries (e.g. China, India and Pakistan are the most common ones). Instead, the impact of illegal transfers of ELVs is a more limited issue, quantified approximately in 2 million tons each year [2]. Final destination of ELVs are both European and extra-European countries.

Again, WEEEs and ELVs have different environmental impacts. In fact, by analysing several works [8], it is possible to say that the overall WEEE's and PCB's impact on the environment (and the human health) is given by the treatment of great amounts of flame-retardants and different types of plastics composing e-wastes, especially PBDE. Instead, from the ELV side, important environmental impacts are due to both metallurgical processes for the recovery of basic metals or the treatment and incineration of the ASR fraction in some nations [9].

The final distinction between WEEEs and ELVs is related to the international literature attention characterizing each of these two waste streams. In fact, before writing this paper, a structured literature review analysing articles covering WEEEs and ELVs and published from 2000 up to the first half of 2015 was implemented. Several terms were used during the assessment (e.g. ELV, WEEE, PCB, automotive, electronics, recycling, remanufacturing, etc.) and researched in titles, abstracts and keywords. In total, 363 scientific and industrial documents focused on WEEEs and PCBs and 246 works focused on ELVs were gathered. Scientific papers were selected through the most popular scientific works search engines (e.g. Google™ Scholar, Sage™, Science Direct™, Springer™, Taylor&Francis™ Online and Wiley™ Online Libraries). The total amount of works acquired (609) reveals the enormous attention devoted to these topics by the experts. Papers consisted in 376 publications in scientific journals with impact factor, 60 in scientific journals without impact factor, 82 in proceedings of scientific conferences, 53 scientific reports, 15 book chapters, and 23 industrial reports. There are several perspectives from which WEEEs, ELVs and PCBs were approached. From the WEEE side, issues related to a more sustainable management of PCBs are a common topic among the experts and almost all papers speaking about PCBs consider WEEEs as the main source [10]. From the ELV side, there is a completely different trend. In fact, even if issues about a more sustainable management of ELVs are well-assessed by the experts (mainly pushed by the advent of more severe directives), the common focus is on alternative ways to recycle the percentage of the car hulk that, currently, is landfilled of incinerated [5]. This means that also the literature preferred to consider a weighted-based principle followed by the ELV Directive instead of focusing on a better exploitation of valuable elements embedded into ELVs. This way, automotive PCBs were rarely considered by the experts and data about them are nowadays hardly gatherable.

3. WEEEs versus ELVs - commonalities

A common point between WEEEs and ELVs is represented by PCBs. Recent works [6, 11] verified that scrap automotive PCBs are, in effect, very similar to PCBs coming from e-wastes. Consequently, it is possible to consider the same technological process for their treatment [12]. In general, this process can be seen as the sum of six main phases that, starting from waste PCBs, allow to obtain a set of (almost pure) raw materials as final output. These phases can be distinguished into: collection, pre-treatment, disassembly, shredding, separation and refining [13, 14, 15] – see Figure 3. Initially, PCBs are collected from different actors (e.g. used PCB traders, treatment facilities, dismantlers, etc.). After an initial pre-treatment (where waste PCBs are cleaned by the operators), the subsequent disassembly phase allows to remove toxic components present on the main board (e.g. condensers or batteries) by addressing them to specific treatment plants. During the shredding phase, waste PCBs are crushed into micro pieces up to become a uniform powder through several machines (e.g. shredders, grinders, hammer mills, etc.). When the correct granularity is reached, the powder is separated basing on its composition (technologies do that by exploiting physical and chemical characteristics of the powder), dividing metal from non-metal powders [16]. Nowadays, these last ones are destined to landfills, however there are interesting works studying alternative (and valuable) ways to reuse them for different purposes [17]. Finally, metal powders are refined through different technologies (e.g. pyrolysis, pyrometallurgy, hydrometallurgy, biometallurgy) up to obtain almost pure secondary resources [18].

However, before the treatment of any kind of waste PCBs, a materials' characterization phase always occurs. This means a definition of the set of materials embedded in a certain

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amount of PCBs, by chemically analysing a sample of them. This phase allows to: (i) comprehend the presence (or not) of valuable materials, and (ii) define the expected revenues coming from their recovery.

From the WEEEs perspective, information about the materials characterization of PCBs embedded on them is widely available in the literature [10]. Generally, WEEEs are classified into ten categories (please, see the WEEE Directive for details) depending on the reference typology. Basing on each category, the literature already classified the type of PCB embedded into products. Table 1 reports a short list of materials embedded into three types of PCBs from mass electronics.

Table 1. Characterization of mass electronics PCBs – source [10]

Material	Cat1 (%)	Cat2 (%)	Cat3 (%)
Silver (Ag)	0.02	0.17	0.08
Gold (Au)	0.002	0.04	0.01
Copper (Cu)	11.0	20.0	17.25

From the automotive perspective, a PCBs characterization was implemented into a different way. Data were gathered from an official industrial source, the IMDS database. Data related to almost 500 different automotive electronic devices were categorized into four typologies, deriving from the weights distribution. In fact, waste automotive PCBs are very different in size, shape and composition terms, depending on their functionality [6]. Hence, a subdivision like the one followed for WEEEs could be not significant. Table 2 reports a short list of materials embedded into these four PCBs categories.

Table 2. Characterization of automotive PCBs – source [28]

Material	Cat1 (%)	Cat2 (%)	Cat3 (%)	Cat4 (%)
Silver (Ag)	0.09	0	0	0
Gold (Au)	0.42	0.20	0.24	0.09
Copper (Cu)	18.84	24.19	14.52	16.30

By comparing Table 1 and Table 2, it is possible to confirm that the materials composition of PCBs embedded into WEEEs and ELVs is not so different. The only distinction lies in materials amounts (e.g. precious metals), with a great impact on profitability of the recovery process.

PCBs, as already defined at the beginning of Section 5, are the most important link between WEEEs and ELVs. Given that these are the two main sources of waste worldwide, automatically they can be considered also as the two main sources of waste PCBs. Their volumes are impressive and comparable. In fact, even if PCBs account for a limited percentage of the overall weight in both WEEEs and ELVs (3% - 6% [19, 20] and 0.1% - 0.7% [21, 22] respectively), their volumes are quantifiable in terms of kilotons per year. Obviously, growth rates directly follows the ones predicted for both WEEEs and ELVs by several experts [1, 2]. For example, in the EU28 these volumes can be accountable in about 167 Ktons/year and 17 Ktons/year for WEEEs and ELVs respectively, by taking into account 2015 predictions. These impressive amounts of PCB volumes, together with the percentage of valuable materials embedded into them described in Section 5.2, can offer a picture of what enormous revenues could be achieved if these resources could be recovered in a correct way.

Another topic that, after PCBs, better links WEEEs and ELVs relates to hybrid and electric vehicles. In fact, this types of cars, that are becoming even more common in our streets, see a high presence of electric and electronic equipments embedded into a vehicle, with a great use of valuable and critical materials (e.g. precious group metals – PGMs in PCBs, rare earth elements – REEs in electric motors and batteries, aluminium and magnesium in frames) [23]. This way, once the car will reach its end of life, these vehicles could become a very important source of materials. Many authors already started to study this phenomena [24] and some companies implemented some first examples of dedicated recovery plants (especially for batteries recycling) [25]. However, as in other industrial fields, recovery targets are still very limited and international regulations have not yet started to regulate them within current ELV directives [26].

Another common point is related to PCBs management issues [27, 21]. An absence of explicit regulations concerning their treatment, physical characteristics, treatment technologies and an absence of limitations about the export of PCBs are only some of the discussion topics. From the first side, even if PCBs are re-known to be the most important component into e-wastes (and among one of the most important in cars), there are no explicit regulations concerning their treatment. Directives speak about them as hazardous components (like batteries, air bags, condensers, fuels, filters, etc.) that must be treated separately from the main recycling process of e-wastes and ELVs, but there are no details about specific recovery levels that have to be reached by authorized centres. From the second side, physical characteristics (e.g. materials layering, components miniaturization, current safety regulations) of PCBs limit the chances to recover 100% of materials, and a great part of them is unintentionally lost during mechanical treatments, heating phases or chemical reactions. From the third side, common technologies used for the treatment of PCBs are taken from the mining sector. This way, their focus is on quantity (and not quality) optimization and recovery rates hardly exceed 20% - 30% of materials in input. From the fourth side, given what established by current directives, there are no limitations to the export of PCBs from one European nation to another. This way, local resources that could be maintained within national borders (with positive effects for the overall local industrial context) are transferred abroad, by implicitly denying any sort of new entrepreneurial initiative in this context.

4. Discussion

After having described all the possible common and distinguishing points of WEEEs and ELVs it is important to discuss what could be the main results coming from a unified management of waste PCBs from both these two sources. This means a quantification of potential volumes and profits and the analysis of their expected trends, for example within the next 15 years. To this aim, the procedure followed for their calculation was taken from [28].

From a WEEEs side, these data were directly gathered both from Eurostat and the literature [10, 19, 20]. After, it was possible to predict the expected profits (in a min – max range). These profits were gathered by multiplying the average weight of each material – in comparison with the overall PCB average mass – by their unitary profits (€/kg) obtained by considering both materials market prices, a set of costs characterizing a reference PCBs recovery process, and a purity level equal to the one required by the market for virgin resources. Table 3 reports the main data derived from the calculation procedure.

Table 3: Estimates of profits from European WEEEs - Sources: [10, 28, 29]

	2015	2020	2030
EU total PCBs expected Net Present Values – min values (M€)	2,536	2,939	3,950
EU total PCBs expected Net Present Values – max values (M€)	5,013	5,811	7,810

From an ELVs side, data were gathered directly from the literature [2, 29]. Then, ELV volumes were distinguished into premature and natural ones. Premature ELVs – representing almost 20% of total volumes generated annually [30, 31] – were hypothesised to be completely recovered. Instead, natural ELVs – representing the 80% of the total amount of annual ELVs volumes [26, 32] – were hypothesised to be partially remanufactured. This assumption caused a reduction in annual ELV volumes, accountable by the experts in about 20% - 30% of the overall amount of ELVs [26, 33]. Once defined the average mass of an ELV, the initial amount of vehicles was translated in million tons and, then, divided between premature and natural ELVs amounts. The following step was the definition of the average PCBs mass (in percentage) out of the total ELV mass, starting from IMDS data. Given both the average ELV and PCB mass, a ratio was established (estimated in about 0.1% - 0.7% [21, 22]) and directly used to quantify annual generated volumes of PCBs from ELVs. Finally, it was possible to predict the expected profits (in a min – max range). This last phase followed the same principle previously described for WEEEs. Table 4 reports the main data derived from the calculation procedure.

Table 4: Estimates of profits from European ELVs - Source [2, 5, 26, 28, 30]

	2015	2020	2030
EU total PCBs expected Net Present Values – min values (M€)	891	978	1,125
EU total PCBs expected Net Present Values – max values (M€)	8,412	9,235	10,628

By considering together Table 3 and Table 4, it is possible to have a picture, even if only hypothetical, of the potential dimension of the overall PCBs recovery market in the only Europe. Even if volumes of PCBs from WEEEs are an order of magnitude greater than the ones from ELVs, by considering Table 1 and Table 2 these last ones could be more profitable on average, given the higher content in precious metals. Potentially reachable profits could go from 3.43 billion € to 5.08 billion € as minimum levels and from 13.43 billion € to 18.44 billion € as maximum level.

These numbers, even if theoretical, demonstrate the utmost importance related to the joined management of PCBs and the economic impact that could be potentially achieved in the next future (or it is currently lost, by seeing the only 2015 data). In addition, by considering current evolutions of transportation means towards hybrid and electric technologies and autonomous-guided systems, the use of electronics within cars is destined to further increase in the next decades [34, 35]. This way, once the car will reach its end of life, these vehicles could become a very important source of materials.

Many authors already started to study this phenomena [24, 36] and some companies implemented first examples of dedicated recovery plants (especially for batteries) [25]. However, as in other industrial fields, recovery targets are still very limited and international regulations have not yet started to regulate them within current ELV directives [26]. Given this additional trend, previously reported data could be even lower than the real ones. Without any doubt, this market sector could become an interesting business for many companies involved with a different role in closed-loop supply chains.

5. Conclusions

The structured literature review presented within this paper demonstrated as there are good chances to manage similar waste PCBs coming from different waste sources in a common way. From one side, this could limit the investment efforts required to industrial actors and, from the other one, it could favour an increase in revenues and counterbalance the treatment of non-profitable cores. Furthermore, also from a governmental point of view, the integrated management of similar wastes could simplify regulations and improve the overall sustainability of End of Life (EoL) processes. Interesting researches could consider the assessment of technological requirements for the real implementation of the ideas presented within this paper, the assessment of potential environmental impacts and the definition of innovative reverse logistic chains. Instead, the next steps of this work will be the exploitation of commonalities between WEEEs and ELVs for the definition of innovative EoL business models.

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Paolo Rosa[a,*] and Sergio Terzi[a]

Politecnico di Milano, Department of Management, Economics and Industrial Engineering
Piazza Leonardo Da Vinci 32, 20133 Milano - Italy

* Corresponding author. Tel.: +39-02-2399-9537; fax: +39-02-2399-2730. *E-mail address:* paolo1.rosa@polimi.it

Abstract

Waste Electrical and Electronic Equipments (WEEEs) and End of Life Vehicles (ELVs) are two of the main waste streams, after municipal solid wastes, both in volumes and growth rates terms. Even if their management begins to be adequately regulated almost worldwide, there are still clear lacks to be solved in many aspects. The aim of this paper is the comparison, through a structured literature analysis, of these waste streams under several perspectives, by evidencing current differences and potential commonalities. In addition, a quantification of potential profits rising from a joined management of different sources of PCBs is described in the last part of the paper.
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Keywords: Waste Electrical and Electronic Equipments; End of Life Vehicles; Printed Circuit Boards; Literature Review, Potential profits.

1. Introduction

End of Life Vehicles (ELVs), together with Waste Electrical and Electronic Equipments (WEEEs), are two of the main sources of secondary raw materials. Yearly, impressive amounts of wastes, quantified in several million tons by different experts and organizations (e.g. [1, 2]), are generated worldwide. Given the continuous increase of these volumes, during the last decades many international directives were introduced, trying to regulate flows of materials both landfilled and illegally shipped abroad. However, the adopted approaches favoured the only recovery of basic materials.

Nomenclature

ASR Automotive Shredder Residue
ELV End of Life Vehicle
EoL End of Life
PCB Printed Circuit Board
WEEE Waste Electrical and Electronic Equipment

This way, many critical issues (a short list of them is reported here) raised during the years:

- A continuous landfilling of valuable resources;
- A common use of non-sustainable design procedures during the product development process;
- An absence of political support on investments in new recovery plants;
- A low performance level reached by current recycling technologies;
- A strong disaggregation of reverse logistic chains;
- A current focus on basic materials recovery;
- An absence of best practices and innovative business models.

The aim of this paper is the comparison, through a structured literature analysis, of WEEE and ELV waste streams under several perspectives, by evidencing current differences and potential commonalities. In addition, a quantification of potential profits rising from a joined management of PCBs from different waste streams is described in the last part of the paper.

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The paper is organized as follows: Section 2 presents a series of distinguishing points about the current management of WEEEs and ELVs. Section 3 assesses existing commonalities of these two waste streams. A quantification of potential profits and a discussion of results is conducted in Section 4. Section 5 presents some concluding remarks and future perspectives.

2. WEEEs versus ELVs - distinguishing points

WEEEs and ELVs are the two main sources of waste. However, their evolution followed different paths. The recycling of ELVs is a process existing since the '60s, and the reuse of scrap metals is not a new idea. Instead, the recycling of WEEEs is a modern process, developed since the '90s. Even if technologies applied in these two processes are similar (at least at macro level) their evolution brought to different focuses and performances. The management of waste PCBs is an important example going into this direction.

From the WEEE side [3, 4], consumer and industrial wastes are collected by formal actors (public or private collection points) and directly transferred to authorized treatment facilities. Here, depending on the type of WEEE, these are disassembled up to divide valuable components and hazardous elements. Both valuable and hazardous components are stored and, then, transferred to dedicated recycling plants. The remaining WEEE mass is directly shredded and separated onsite up to recover basic materials (e.g. construction metals, plastics, wood, glass, concrete, etc.) – see Figure 1. Being PCBs one of the most valuable components, they are separated from the wasted product during disassembly, classified, stored and transferred to dedicated plants for the final recovery of precious metals.

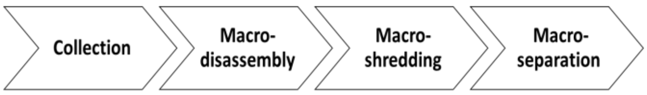

Figure 1. A typical WEEE recycling process – Adapted from [3]

From the ELVs side, cars can be distinguished into two main groups, premature and natural ELVs. Premature ELVs are cars that reached their End of Life phase because of a big accident. Instead, natural ELVs are cars reaching the End of their Life because of obsolescence. Whatever the ELV type, they are collected in many different ways (e.g. official dealers, body shops, auto wreckers, etc.). Then, they are deleted from the public register and depolluted from the main pollutant and hazardous components (e.g. batteries, fuel, oils, filters, etc.). Subsequently, most valuable parts (e.g. engines, catalysts, radiators, gearboxes, etc.) - if functioning - are disassembled and reused as spare parts in the secondary market. The car hulk is, then, crushed and fragmented into little scraps. At the end, these scraps are separated by exploiting their physical characteristics (e.g. density, weight, magnetism, etc.) up to obtain a uniform amount of materials. In general, the metal part is directly reintroduced in the automotive supply chain (as input material for foundries). Instead, the non-metal part (generally named Auto Shredder Residue - ASR) is currently landfilled or used as fuel for energy generation purposes [5] – see Figure 2. Information about non-reusable automotive PCBs are rare to find in literature. However (with a good approximation), it is possible to say that, if not disassembled from the car, automotive PCBs are crushed together with car hulks [6]. An important distinction between WEEEs and ELVs is present also in terms of strategies followed during the end of their life. In fact, recycling is the preferred strategy for the management of WEEE components [1] and remanufacturing the most common one for ELV components [7]. Undoubtedly, this distinction relates to the intrinsic value of cores. In fact, components embedded into WEEEs are, generally, low / medium value elements and their remanufacturing would not allow to re-enter from sustained costs. As opposite, automotive components (especially the mechatronic ones) have a very high value (because of their complexity) and the demand coming from the secondary market is well-developed. This way, remanufacturing costs are completely covered by revenues, so guaranteeing good profits to the actors involved in these activities. A reference market for remanufactured parts is in the USA.

Figure 2. A typical ELV recycling process – Adapted from [5]

Figure 3. A typical PCB recycling process – Adapted from [13]

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The illegal shipment of great amounts of scrap products abroad is another issue characterizing both WEEEs and ELVs. However, volumes and final destinations are very different. From the WEEE point of view, illegal flows reach approximately 50% of volumes generated yearly in the world. This means that, by considering a global annual amount going from 30 to 50 million tons of WEEEs [1], illegal shipments reach approximately 15-25 million tons. Furthermore, their destinations are well-known by the experts, and represented by several developing countries (e.g. China, India and Pakistan are the most common ones). Instead, the impact of illegal transfers of ELVs is a more limited issue, quantified approximately in 2 million tons each year [2]. Final destination of ELVs are both European and extra-European countries.

Again, WEEEs and ELVs have different environmental impacts. In fact, by analysing several works [8], it is possible to say that the overall WEEE's and PCB's impact on the environment (and the human health) is given by the treatment of great amounts of flame-retardants and different types of plastics composing e-wastes, especially PBDE. Instead, from the ELV side, important environmental impacts are due to both metallurgical processes for the recovery of basic metals or the treatment and incineration of the ASR fraction in some nations [9].

The final distinction between WEEEs and ELVs is related to the international literature attention characterizing each of these two waste streams. In fact, before writing this paper, a structured literature review analysing articles covering WEEEs and ELVs and published from 2000 up to the first half of 2015 was implemented. Several terms were used during the assessment (e.g. ELV, WEEE, PCB, automotive, electronics, recycling, remanufacturing, etc.) and researched in titles, abstracts and keywords. In total, 363 scientific and industrial documents focused on WEEEs and PCBs and 246 works focused on ELVs were gathered. Scientific papers were selected through the most popular scientific works search engines (e.g. Google™ Scholar, Sage™, Science Direct™, Springer™, Taylor&Francis™ Online and Wiley™ Online Libraries). The total amount of works acquired (609) reveals the enormous attention devoted to these topics by the experts. Papers consisted in 376 publications in scientific journals with impact factor, 60 in scientific journals without impact factor, 82 in proceedings of scientific conferences, 53 scientific reports, 15 book chapters, and 23 industrial reports. There are several perspectives from which WEEEs, ELVs and PCBs were approached. From the WEEE side, issues related to a more sustainable management of PCBs are a common topic among the experts and almost all papers speaking about PCBs consider WEEEs as the main source [10]. From the ELV side, there is a completely different trend. In fact, even if issues about a more sustainable management of ELVs are well-assessed by the experts (mainly pushed by the advent of more severe directives), the common focus is on alternative ways to recycle the percentage of the car hulk that, currently, is landfilled of incinerated [5]. This means that also the literature preferred to consider a weighted-based principle followed by the ELV Directive instead of focusing on a better exploitation of valuable elements embedded into ELVs. This way, automotive PCBs were rarely considered by the experts and data about them are nowadays hardly gatherable.

3. WEEEs versus ELVs - commonalities

A common point between WEEEs and ELVs is represented by PCBs. Recent works [6, 11] verified that scrap automotive PCBs are, in effect, very similar to PCBs coming from e-wastes. Consequently, it is possible to consider the same technological process for their treatment [12]. In general, this process can be seen as the sum of six main phases that, starting from waste PCBs, allow to obtain a set of (almost pure) raw materials as final output. These phases can be distinguished into: collection, pre-treatment, disassembly, shredding, separation and refining [13, 14, 15] – see Figure 3. Initially, PCBs are collected from different actors (e.g. used PCB traders, treatment facilities, dismantlers, etc.). After an initial pre-treatment (where waste PCBs are cleaned by the operators), the subsequent disassembly phase allows to remove toxic components present on the main board (e.g. condensers or batteries) by addressing them to specific treatment plants. During the shredding phase, waste PCBs are crushed into micro pieces up to become a uniform powder through several machines (e.g. shredders, grinders, hammer mills, etc.). When the correct granularity is reached, the powder is separated basing on its composition (technologies do that by exploiting physical and chemical characteristics of the powder), dividing metal from non-metal powders [16]. Nowadays, these last ones are destined to landfills, however there are interesting works studying alternative (and valuable) ways to reuse them for different purposes [17]. Finally, metal powders are refined through different technologies (e.g. pyrolysis, pyrometallurgy, hydrometallurgy, biometallurgy) up to obtain almost pure secondary resources [18].

However, before the treatment of any kind of waste PCBs, a materials' characterization phase always occurs. This means a definition of the set of materials embedded in a certain amount of PCBs, by chemically analysing a sample of them.

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This phase allows to: (i) comprehend the presence (or not) of valuable materials, and (ii) define the expected revenues coming from their recovery.

From the WEEEs perspective, information about the materials characterization of PCBs embedded on them is widely available in the literature [10]. Generally, WEEEs are classified into ten categories (please, see the WEEE Directive for details) depending on the reference typology. Basing on each category, the literature already classified the type of PCB embedded into products. Table 1 reports a short list of materials embedded into three types of PCBs from mass electronics.

Table 1. Characterization of mass electronics PCBs – source [10]

Material	Cat1 (%)	Cat2 (%)	Cat3 (%)
Silver (Ag)	0.02	0.17	0.08
Gold (Au)	0.002	0.04	0.01
Copper (Cu)	11.0	20.0	17.25

From the automotive perspective, a PCBs characterization was implemented into a different way. Data were gathered from an official industrial source, the IMDS database. Data related to almost 500 different automotive electronic devices were categorized into four typologies, deriving from the weights distribution. In fact, waste automotive PCBs are very different in size, shape and composition terms, depending on their functionality [6]. Hence, a subdivision like the one followed for WEEEs could be not significant. Table 2 reports a short list of materials embedded into these four PCBs categories.

Table 2. Characterization of automotive PCBs – source [28]

Material	Cat1 (%)	Cat2 (%)	Cat3 (%)	Cat4 (%)
Silver (Ag)	0.09	0	0	0
Gold (Au)	0.42	0.20	0.24	0.09
Copper (Cu)	18.84	24.19	14.52	16.30

By comparing Table 1 and Table 2, it is possible to confirm that the materials composition of PCBs embedded into WEEEs and ELVs is not so different. The only distinction lies in materials amounts (e.g. precious metals), with a great impact on profitability of the recovery process.

PCBs, as already defined at the beginning of Section 5, are the most important link between WEEEs and ELVs. Given that these are the two main sources of waste worldwide, automatically they can be considered also as the two main sources of waste PCBs. Their volumes are impressive and comparable. In fact, even if PCBs account for a limited percentage of the overall weight in both WEEEs and ELVs (3% - 6% [19, 20] and 0.1% - 0.7% [21, 22] respectively), their volumes are quantifiable in terms of kilotons per year. Obviously, growth rates directly follows the ones predicted for both WEEEs and ELVs by several experts [1, 2]. For example, in the EU28 these volumes can be accountable in about 167 Ktons/year and 17 Ktons/year for WEEEs and ELVs respectively, by taking into account 2015 predictions. These impressive amounts of PCB volumes, together with the percentage of valuable materials embedded into them described in Section 5.2, can offer a picture of what enormous revenues could be achieved if these resources could be recovered in a correct way.

Another topic that, after PCBs, better links WEEEs and ELVs relates to hybrid and electric vehicles. In fact, this types of cars, that are becoming even more common in our streets, see a high presence of electric and electronic equipments embedded into a vehicle, with a great use of valuable and critical materials (e.g. precious group metals – PGMs in PCBs, rare earth elements – REEs in electric motors and batteries, aluminium and magnesium in frames) [23]. This way, once the car will reach its end of life, these vehicles could become a very important source of materials. Many authors already started to study this phenomena [24] and some companies implemented some first examples of dedicated recovery plants (especially for batteries recycling) [25]. However, as in other industrial fields, recovery targets are still very limited and international regulations have not yet started to regulate them within current ELV directives [26].

Another common point is related to PCBs management issues [27, 21]. An absence of explicit regulations concerning their treatment, physical characteristics, treatment technologies and an absence of limitations about the export of PCBs are only some of the discussion topics. From the first side, even if PCBs are re-known to be the most important component into e-wastes (and among one of the most important in cars), there are no explicit regulations concerning their treatment. Directives speak about them as hazardous components (like batteries, air bags, condensers, fuels, filters, etc.) that must be treated separately from the main recycling process of e-wastes and ELVs, but there are no details about specific recovery levels that have to be reached by authorized centres. From the second side, physical characteristics (e.g. materials layering, components miniaturization, current safety regulations) of PCBs limit the chances to recover 100% of materials, and a great part of them is unintentionally lost during mechanical treatments, heating phases or chemical reactions. From the third side, common technologies used for the treatment of PCBs are taken from the mining sector. This way, their focus is on quantity (and not quality) optimization and recovery rates hardly exceed 20% - 30% of materials in input. From the fourth side, given what established by current directives, there are no limitations to the export of PCBs from one European nation to another. This way, local resources that could be maintained within national borders (with positive effects for the overall local industrial context) are transferred abroad, by implicitly denying any sort of new entrepreneurial initiative in this context.

4. Discussion

After having described all the possible common and distinguishing points of WEEEs and ELVs it is important to discuss what could be the main results coming from a unified management of waste PCBs from both these two sources. This means a quantification of potential volumes and profits and the analysis of their expected trends, for example within the next 15 years. To this aim, the procedure followed for their calculation was taken from [28].

From a WEEEs side, these data were directly gathered both from Eurostat and the literature [10, 19, 20]. After, it was possible to predict the expected profits (in a min – max range). These profits were gathered by multiplying the average weight of each material – in comparison with the overall PCB average mass – by their unitary profits (€/kg) obtained by considering both materials market prices, a set of costs characterizing a reference PCBs recovery process, and a purity level equal to the one required by the market for virgin resources. Table 3 reports the main data derived from the calculation procedure.

Table 3: Estimates of profits from European WEEEs - Sources: [10, 28, 29]

	2015	2020	2030
EU total PCBs expected Net Present Values – min values (M€)	2,536	2,939	3,950
EU total PCBs expected Net Present Values – max values (M€)	5,013	5,811	7,810

From an ELVs side, data were gathered directly from the literature [2, 29]. Then, ELV volumes were distinguished into premature and natural ones. Premature ELVs – representing almost 20% of total volumes generated annually [30, 31] – were hypothesised to be completely recovered. Instead, natural ELVs – representing the 80% of the total amount of annual ELVs volumes [26, 32] – were hypothesised to be partially remanufactured. This assumption caused a reduction in annual ELV volumes, accountable by the experts in about 20% - 30% of the overall amount of ELVs [26, 33]. Once defined the average mass of an ELV, the initial amount of vehicles was translated in million tons and, then, divided between premature and natural ELVs amounts. The following step was the definition of the average PCBs mass (in percentage) out of the total ELV mass, starting from IMDS data. Given both the average ELV and PCB mass, a ratio was established (estimated in about 0.1% - 0.7% [21, 22]) and directly used to quantify annual generated volumes of PCBs from ELVs. Finally, it was possible to predict the expected profits (in a min – max range). This last phase followed the same principle previously described for WEEEs. Table 4 reports the main data derived from the calculation procedure.

Table 4: Estimates of profits from European ELVs - Source [2, 5, 26, 28, 30]

	2015	2020	2030
EU total PCBs expected Net Present Values – min values (M€)	891	978	1,125
EU total PCBs expected Net Present Values – max values (M€)	8,412	9,235	10,628

By considering together Table 3 and Table 4, it is possible to have a picture, even if only hypothetical, of the potential dimension of the overall PCBs recovery market in the only Europe. Even if volumes of PCBs from WEEEs are an order of magnitude greater than the ones from ELVs, by considering Table 1 and Table 2 these last ones could be more profitable on average, given the higher content in precious metals. Potentially reachable profits could go from 3.43 billion € to 5.08 billion € as minimum levels and from 13.43 billion € to 18.44 billion € as maximum level.

These numbers, even if theoretical, demonstrate the utmost importance related to the joined management of PCBs and the economic impact that could be potentially achieved in the next future (or it is currently lost, by seeing the only 2015 data). In addition, by considering current evolutions of transportation means towards hybrid and electric technologies and autonomous-guided systems, the use of electronics within cars is destined to further increase in the next decades [34, 35]. This way, once the car will reach its end of life, these vehicles could become a very important source of materials.

Many authors already started to study this phenomena [24, 36] and some companies implemented first examples of dedicated recovery plants (especially for batteries) [25]. However, as in other industrial fields, recovery targets are still very limited and international regulations have not yet started to regulate them within current ELV directives [26]. Given this additional trend, previously reported data could be even lower than the real ones. Without any doubt, this market sector could become an interesting business for many companies involved with a different role in closed-loop supply chains.

5. Conclusions

The structured literature review presented within this paper demonstrated as there are good chances to manage similar waste PCBs coming from different waste sources in a common way. From one side, this could limit the investment efforts required to industrial actors and, from the other one, it could favour an increase in revenues and counterbalance the treatment of non-profitable cores. Furthermore, also from a governmental point of view, the integrated management of similar wastes could simplify regulations and improve the overall sustainability of End of Life (EoL) processes. Interesting researches could consider the assessment of technological requirements for the real implementation of the ideas presented within this paper, the assessment of potential environmental impacts and the definition of innovative reverse logistic chains. Instead, the next steps of this work will be the exploitation of commonalities between WEEEs and ELVs for the definition of innovative EoL business models.

Acknowledgements

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Ref.: Ms. No. PROCIR-S-15-02338

Waste Electrical and Electronic Equipments versus End of Life Vehicles: a state of the art analysis and quantification of potential profits

Dear Reviewers,

Thank you very much for your informed comments, which helped to improve this paper to the right standard considered for publication. We appreciated the time you spent in doing this. We tried to address all the issues you mentioned.
My colleague and I have revised the paper basing on your valuable comments. I hope that now we will be able to reach the expected standard, worthy of publication in this journal.

A list of the answers to your precious suggestions is reported below.

Many thanks for your time and comments.

Reviewer #1: 1° comment

The paper is essentially a categorization of papers published on the topic of electronic and electric vehicle waste. It does not really add anything to the field but "organizes" work already published by others. it is, to my reading, similar to what a good MS thesis would have as a literature review.

Response

A discussion section was added to the initial work, trying to improve this lack.

Reviewer #1: 2° comment

It is useful in pointing out some of the flows and challenges of recycling or recovery.

Response

Please, see the previous comment.

Reviewer #1: 3° comment

The paper is written in a very casual style with no particular scientific content.

Response

A complete revision of both paper's structure and contents was done by the authors.

Reviewer #2: 1° comment

Page 3 - last section: „From the ELVs side, cores can be …" should be replace by „From the ELVs side, cars can be …"

Response

Done, thanks for your comment.

Reviewer #2: 2° comment

Page 4 - Figure 4 takes a lot of space at page 3 and text size is very small / hard to read -> this should be modified

Response

Done, thanks for your comment.

Reviewer #2: 3° comment

Page 5 - table 1: The reference of UNEP report should be mentioned

Response

Done, thanks for your comment.

Reviewer #2: 4° comment

Page 5 - table 2: the reference of the IMDS database should be mentioned

Response

Done, thanks for your comment.