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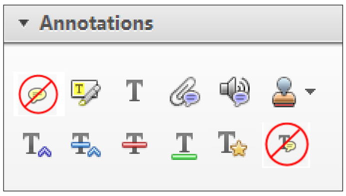


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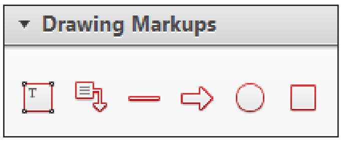


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# Scrap automotive electronics: A mini-review of current management practices

**Federica Cucchiella[1], Idiano D'Adamo[1], Paolo Rosa[2] and Sergio Terzi[2]**

**Abstract**

End-of-life vehicles, together with waste from electric and electronic equipment, are known as an important source of secondary raw materials. For many years, their recovery has allowed the restoring of great amounts of metals for new cars production. This article provides a comprehensive mini-review on the end-of-life vehicles recycling topic between 2000 and 2014, with a particular focus on automotive electronics recycling. In fact, in the last years, experts focused their attention on a better exploitation of automotive shredder residue fraction, but not sufficiently on eventual electronic scraps embedded in it. Hence, studies assessing the value embedded in these scraps are rarely available in literature, causing an important gap in both recycling policies and research. The fact that, at present, the management of electronic control units (the most valuable component among automotive electronic equipment) is, as yet, off the radar in both end-of-life vehicles and waste from electric and electronic equipment Directives demonstrates the theory. Of course, their recycling would not contribute in a relevant way to reach the weighted-based recycling and recovery targets characterising current regulations, but would be very important under a critical raw materials recovery view. Results coming from the literature analysis confirm these assumptions.

**Keywords**

Electronic control units, end-of-life vehicles, literature review, recycling, sustainability

## Introduction

Every day, a lot of wastes are produced by citizens and firms, causing serious environmental damages. However, the international scientific community is aware of these issues, by continuously pushing manufacturers on the adoption of several sustainability opportunities, as ecological concerns, social responsibility policies and development of sustainable products (Cucchiella et al., 2012; Li, 2015; Pérez-Belis et al., 2015). Even nations and supranational entities are on the topic. Owing to the increasing scarcity of raw materials around the world (Clappier et al., 2014; Kohlmeyer, 2012; Kunze, 2012), different nations are going to develop or improve their regulations about the sustainable management of valuable waste streams. Consequently, end-of-life (EoL) strategies have become mandatory for the sustainability improvement of products and production systems (Cucchiella et al., 2015a; Hiratsuka et al., 2014).

The automotive sector is one of the most important sources of waste, not only because of precious metals and critical materials embedded into end-of-life vehicles (ELVs) (Berzi et al., 2013; Uan et al., 2007; United Nations Environment Programme, 2013), but also in terms of volumes (in Europe, the total ELVs annual generation is expected to reach 15.4 million tonnes in 2015 and 19.5 million tonnes in 2020) (Sakai et al., 2014; Tian and Chen, 2014; Zorpas and Inglezakis, 2012). [AQ: 1]

To this aim, basic guidelines for the reuse, recovery and recycling of ELVs were established all over the world in the last decades (EC, 2000, 2005, 2013). These directives try to regulate and control the management of ELVs for a correct and sustainable dismantling and recovery of secondary resources (Demirel et al., 2014). Lots of articles analysed and compared different ELV directives and recovery systems around the world (Sakai et al., 2014; Zhao and Chen, 2011), by enhancing weaknesses and strengths, by proposing interesting amendments. However, the recycling of automotive electronics (e.g. electronic control units (ECUs)), together with its environmental impacts, does not appears to have been adequately assessed (Wang and Chen, 2012, 2013b).

The aim of this article is the assessment of the existing lacks in EoL ECU management, trying to define future innovative research streams allowing experts to better focus their efforts in the sustainable management of valuable wastes. However, these contents could be also useful for both politicians and industrials

[1]Department of Industrial and Information Engineering and Economics, University of L'Aquila, L'Aquila, Italy
[2]Department of Management, Economics, and Industrial Engineering, Politecnico di Milano, Milano, Italy

**Corresponding author:**
Federica Cucchiella, Department of Industrial and Information Engineering and Economics, University of L'Aquila, Via G. Gronchi 18, 67100 L'Aquila, Italy.
Email: federica.cucchiella@univaq.it

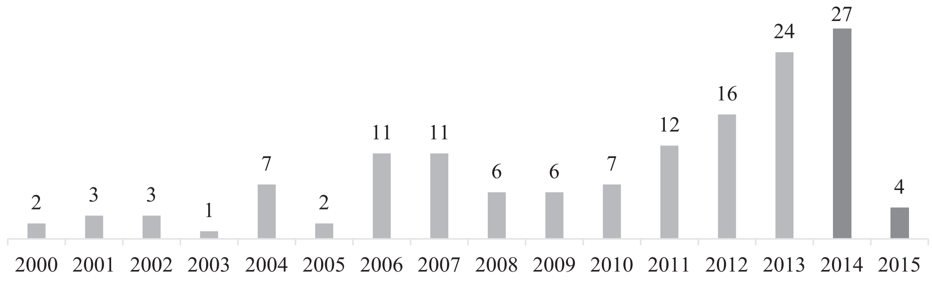


**Figure 1.** Historical series of published articles.

to set optimised regulations and more efficient reverse logistics chains.

## A conceptualisation of the topic

A product reaches the end of its useful life for a series of technological reasons – as obsolescence or deterioration, and for changes in consumer needs (Garetti et al., 2012; Rosa and Terzi, 2014). Recycling is one of the EoL strategies capable of recovering a great part of materials embedded in these products (Cucchiella et al., 2014; Ijomah et al., 1999). When recycling is applied to one of the most important sources of waste, as in case of ELVs, it automatically acquires a central role in sustainable development terms at all levels, from manufacturers to suppliers, from local to national and international economies (Simic and Dimitrijevic, 2012, 2015).

The trend followed by car manufacturers in the last decades, trying to reduce fuel consumption and $CO_2$ emissions, is to lighten vehicles through a massive use of high-resistance steels, aluminium alloys and different types of plastic compounds (Raugei et al., 2014). In parallel, modern cars are becoming even more similar to big e-products, with great amounts of embedded electronic systems able to control almost all the vehicle's functions and virtual connections among cars and the surrounding environment (Kohlmeyer, 2012; Wang and Chen, 2012). This caused a drastic increase in the production of printed circuit boards (PCBs) for automotive purposes (Li et al., 2014; United Nations Environment Programme, 2013). ECUs are among the most valuable electronic devices embedded into 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 (Freiberger et al., 2012; Kripli et al., 2010) 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, 2013a). These last data alone provide evidence of the importance of recovery of the embedded value in these components. [AQ: 2]

## Research methodology and framework of analysis

In a systematic review of the literature, current findings are usually discussed in relation to a particular research question (Achillas et al., 2013; Cucchiella and D'Adamo, 2013), which in this article is represented by ECU recycling. Scientific articles, published from 2000 up to 2014, provided by the most popular academic search engines (e.g. Google Scholar, SAGE, Science Direct, Springer, Taylor&Francis Online and Wiley Online Libraries) have been evaluated. The keyword 'recycling' was combined with different terms (automotive, automotive electronics, electronic control unit, end of life vehicles) and researched in titles, abstracts and keywords of scientific articles (Hiratsuka et al., 2014; Sakai et al., 2014; Vermeulen et al., 2011; Wang and Chen, 2011; Xu et al., 2014).

Figure 1 displays results of the search process, in terms of number of articles per year, and publications trend. The total amount of articles (142) reveals the relevant attention devoted to this topic (from 2000 up to end 2014) by the experts, especially in 2014 and at the beginning of 2015. A total of 92 articles were published in scientific journals with impact factor, 15 in scientific journals without impact factor, 22 in proceedings of scientific conferences, six scientific reports, five book chapters and two industrial reports. [AQ: 3]

The nationality of the articles' first author indicates China as the major contributor, with 21 articles (14.8%), followed by Germany (10.6%), Italy (9.2%), USA (7.0%) and UK (6.3%) (Figure 2). Chinese experts seem to be the most involved in this research field, despite the infancy of the Chinese ELV recycling chain (Zhao and Chen, 2011).

There are several perspectives from which ELV recycling was approached. In macro topic terms, the strategic and economic perspective is the most discussed in literature (26.8%), followed by national recycling systems (13.4%), automotive shredder residue (ASR) treatment and recycling processes (12.0% each), ELV remanufacturing (10.0%), national policies and environmental issues (8.5% each), ELV recycling – other materials (5.6%), ELV recycling – electronics (2.1%) and ELV volumes predictions (1.4%) (Figure 3).

The analysis highlighted a multi-disciplinary topic. For this reason, journals pertain to various research fields and scientific areas. This situation underlines the scarce interest in the international literature about the automotive electronics recycling, even

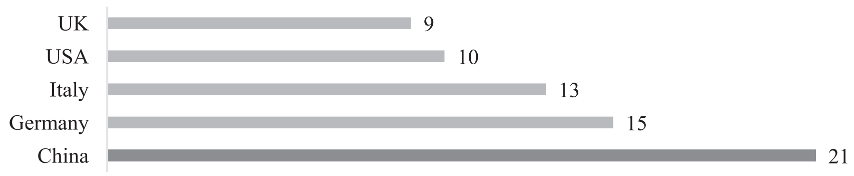


**Figure 2.** Top five publishing countries.

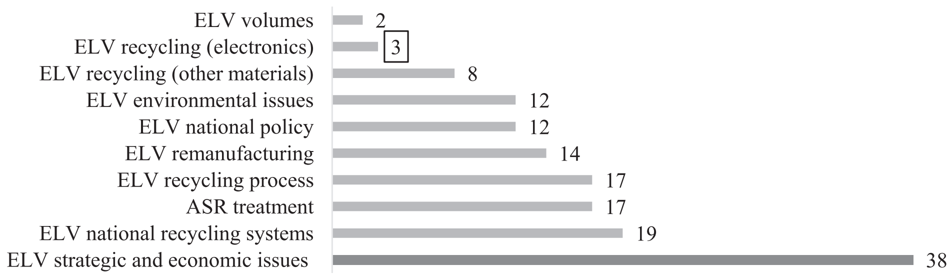


**Figure 3.** ELV recycling macro research areas. [AQ: 26]

if many experts (Berzi et al., 2013; Gerrard and Kandlikar, 2007; Sakai et al., 2014; Vermeulen et al., 2011; Zorpas and Inglezakis, 2012) push on the need to think about this type of waste to reach the updated European ELV directive recovery and recycling levels. This way, the adoption of ECU recycling processes by the automotive recyclers is not supported at all. [AQ: 4]

## Results

The literature review allowed analysis of several aspects of the disposal of ECUs and a list of perspectives can be highlighted:

- ELV policies;
- ECUs EoL strategies;
- ECUs recycling environmental benefits;
- ECUs recycling technological benefits;
- ECUs recycling economic benefits.

### *ELV policies*

The management of ELVs around the world widely differs by a series of variables (e.g. regulations, social structure, political system, economic development) and it can be roughly divided into several geographic macro areas, as Europe, Asia and rest of the world.

*ELV policies in Europe.* The European Union (EU) was one of the first supernational entities to establish a dedicated ELV Directive in 2000 (EC, 2000, 2005, 2013). According to this regulation, each EU member state must ensure that all ELVs generated within its national borders will be treated by authorised treatment facilities (ATFs) for a correct recycling; furthermore, a series of reuse/recovery/recycling rates were set for EU car manufacturers (Blume and Walther, 2013; Ferrão et al., 2006; Lu et al., 2014; Mazzanti and Zoboli, 2006). However, this directive does not specify how to manage each component of a car.

Given the above, EU car manufacturers launched, many years ago, dedicated remanufacturing processes able to manage valuable components (e.g. engines, alternators, transmissions, etc.). In some nations, like in Germany, the remanufacturing industry reached high performances, being able reasonably to reuse or deal with about 90% of the parts dismantled from ELVs (Wang and Chen, 2011; Zorpas and Inglezakis, 2012). However, the ECUs remanufacturing sub-sector remains even very limited, with the presence of only a few independent actors (Kripli et al., 2010; Peters et al., 2014). In parallel to the ECUs management, the resolution of other important issues (e.g. illegal exports control, dedicated informatics tools development, ATFs role and relationship with car manufacturers, standardisation of design for reuse, remanufacturing and recycling (Df3R) rules) could support the improvement of the entire ELVs management sector (Gerrard and Kandlikar, 2007; van Schaik and Reuter, 2004).

Europe is one of the highest producers of ELVs, and the literature estimates an annual generation of 14 million tonnes per year since 2015 (Hiratsuka et al., 2014; Sakai et al., 2014). It is clear that the correct management of this amount of waste could offer great profitability chances to European car remanufacturing and recycling chains, allowing it easily to reach new ELV directive's targets (Kunze, 2012).

*ELV policies in Asia.* From the Asian side, Japan was the first nation to activate ELV legislation in 2005. Its structure is similar to the EU Directive, and virtually covers all vehicle's categories and components (ECUs included). A well-structured reuse/remanufacturing industry was established since some years by Japanese car manufacturers (Hiratsuka et al., 2014; Sakai et al., 2007). In South Korea, the national ELV Directive is coupled with the one related to waste from electric and electronic equipment (WEEE) management. Even in this case, the structure is similar to the EU Directive, but tyres, batteries and air bags are not considered within the automotive components to be recycled (Sakai et al., 2014).

In Taiwan, since 1994, ELV recycling has gradually become systematic. In 2004, the Taiwan Environmental Protection Administration defined a series of ELV guidelines, inserted in the 'Waste Disposal Act', trying to regulate the overall recycling chain. Since then, the recycling channels, processing equipment and techniques for ELVs in Taiwan have gradually become established. However, recycling rates and the ASR management remain lower than in developed countries (Che et al., 2011; Cheng et al., 2012). Finally, China developed an ELV recycling regulation in 2001, enforced in 2006 with a set of more stringent constraints for the management of automotive scraps, expected to reach 13 million tonnes per year by 2020 (Zorpas and Inglezakis, 2012). However, these limits are even lower than the European ones.

*ELV policies in rest of the world.* From the American side, USA is one of the most important nations (together with Canada, Australia and New Zealand) without any form of a federal law on the treatment of ELVs, even if their car market is the largest in the world (Lu et al., 2014; Sakai et al., 2014; Zorpas and Inglezakis, 2012). Fortunately, USA car manufacturers autonomously have shared this responsibility since 1992 and, currently, are able to reach a ELVs recycling rate of about 95% (according to the vehicle's weight). Furthermore, car parts remanufacturing (ECUs included) is a common activity, allowing customers to buy recovered/refurbished spare parts directly from ATFs (Keivanpour et al., 2013; Wang and Chen, 2013c).

## ECUs EoL strategies

In terms of EoL strategies, several articles (Freiberger et al., 2011; Reuter et al., 2006; Steinhilper et al., 2006; Tian and Chen, 2014; Wang and Chen, 2013c) analyse 'where electronic systems end when cars are dismantled'. It is possible to highlight that the destiny of an ECU completely depends on both its market request and structural/functional conditions.

- If ECUs have a high market request and are in a good structural condition, during the dismantling of a car, ATF operators disassemble the specific electronic component (usually, a sub-part of more complex mechatronic systems) and, after a cleaning phase, test the element, by verifying its functional conditions. If the test is positive, the electronic component is re-assembled into the main system and, then, is sold as a 'guaranteed used part' in the spare part market by independent companies or directly by original equipment manufacturers (OEMs). In this case, the environmental impact is almost inexistent if compared with a new product, the value recovery is maximised and the operational costs are very limited (Kripli et al., 2010; Tian and Chen, 2014; Xue et al., 2012).
- If ECUs have a high market request and are in good structural conditions, but do not pass the functional conditions test, they are remanufactured (Subramoniam et al., 2013). During remanufacturing, the product is repaired, re-tested and re-assembled. Then, it is sold as an 'as good as new' product in the spare part market by independent companies or directly by OEMs. Their cost can vary from 50% up to 70% of the corresponding new component, with an energy and resource saving of about 90% when compared with a new part (Kripli et al., 2010; Tian and Chen, 2014; Xue et al., 2012).
- If ECUs do not have a market request and/or are not in good structural conditions, these electronic components are not disassembled at all. This way, they are subsequently crushed and shredded within the car hulk, ending in the ASR fraction (Wang and Chen, 2011). Then, ASR is incinerated to recover the embedded energy or, in the worst case, landfilled (McKenna et al., 2013; Viganò et al., 2010).

Curiously, these three processes act without any assessment of the potential embedded value (in terms of materials content) of treated ECUs by recyclers (Garcia et al., 2015; Go et al., 2011; Park et al., 2014; Xu et al., 2014). This means that some high valuable ECUs in bad structural conditions (and almost all of the low value ECUs) are incinerated or landfilled (as part of ASR fraction), instead of following a more accurate recycling process. This way, a great profit loss for recyclers and waste of valuable resources are lost during thermal and chemical processes. Unfortunately, this lack of any kind of assessment in ECUs recycling is a common issue among nations (Che et al., 2011; Lu et al., 2014; Sakai et al., 2014; Zhao and Chen, 2011).

## Environmental benefits from ECUs recycling

With the rapid growth of vehicle population and electronic control components used in automotives, the energy consumption and environmental emissions of automotive electronic control components reached 20,306,000 tonnes of standard coal equivalent (SCE) in 2007, that is an impressive consumption of energy, and related toxic environmental emissions (Wang et al., 2012).

As ECUs are a particular type of PCBs, similar environmental impacts as the ones widely discussed in literature for these elements are expected. Hence, the presence of tin and lead in solder and components, copper in contacts and circuits, iron and nickel in components and flame-retardant chemicals (e.g. polychlorinated biphenyls) represent the main sources of environmental pollution coming from ECUs (He and Xu, 2014; Wang and Chen, 2012). For example, about 50 g of lead per vehicle can be extracted from medium-sized cars (Wang and Chen, 2011). Avoiding the dispelling of lead (but also copper and nickel) during the ELVs recycling process could allow the reduction of heavy metals contamination in water and soil, and the release of hazardous substances in the environment, especially in countries where environmental protection measures are still under development (Mancini et al., 2014; Zhao and Chen, 2011).

To this aim, the consideration of environmental impacts caused by the increasing use of electronic components in modern cars during the design phase could allow car manufacturers to improve the sustainability of future private transportation systems (Ni and Chen, 2014; Sakai et al., 2014).

## Technological benefits from ECUs recycling

The recycling of ECUs can also offer (even if indirectly) a series of technological benefits. In fact, (Clappier et al., 2014) highlight that an increase in the recovery of scarce raw materials is needed, in order to reach 2015 EU recovery and recycling targets (95% of ELV weight on average). However, up to now, international research did not look into this particular kind of recovery, but strongly focused on the improvement of the ASR management, which is the only part of ELVs commonly considered as the most promising resource to exploit for the increase of recycling performances, mainly because of its huge amount (Taylor et al., 2013; Vermeulen et al., 2011; Zhang and Chen, 2014).

To this aim, experts established two research lines: (i) intensive dismantling, involving the separation and collection of materials at the dismantling stage and (ii) post-shredder treatments involving the collection of materials from ASR fraction, after the shredding stage (Lu et al., 2014; Sakai et al., 2014).

Hence, experts preferred to think about new processes, either before or after the ELV shredding phase. From one side, the intensive dismantling seems to be the most promising strategy because, this way, different components could be correctly transferred to a specific recovery and recycling chain, by reducing the overall generation of ASR as well as its hazardousness (Sakai et al., 2014). However, especially in developed countries, this could imply an increase in dismantling labour costs (Go et al., 2011). From an opposite side, post-shredder treatments have to cope with a big issue, represented by the management of a highly heterogeneous waste stream (Taylor et al., 2013). However, even intensive dismantling is not immune from problems. In fact, as vehicle material's composition changes, higher dismantling/recovery rates are needed to ensure economic viability of the recycling infrastructure (Ferrão et al., 2006; Garcia et al., 2015). Furthermore, even in the case of significantly higher rates of dismantling and plastics recovery, the amount of shredder residue per vehicle will continue to rise (Raboni et al., 2015).

Hence, in order to reach new targets, a higher efficiency in ASR recovery is needed, in addition to material recycling of collectable components and metals (Sakai et al., 2014). This leaves open the doors to innovative ELV dismantling techniques or strategies for the recovery/recycling of parts/materials prior to shredding (Golinska, 2014). As summarised by Kohlmeyer (2012), one way to improve the ASR recycling could be the correct management of a vehicle's increasing computerisation before it becomes an issue in the near future (e.g. in hybrid, electric and hydrogen cars). In fact, the use of rare metals and hazardous substances for computer-related components have further made ASR recycling difficult (Sakai et al., 2014) and the presence of metal–plastic composites and flame-retardant chemicals (e.g. polychlorinated biphenyls) in vehicle's electronic components require high temperatures to separate and recover valuable materials (Lee et al., 2015). These factors are considered significant obstacles to polymer processing and, so, to the improvement of recycling performances (Gerrard and Kandlikar, 2007; Tian and Chen, 2014).

## Economic benefits from ECUs recycling

The economic benefits coming from the reuse and recycle of ECUs have already been proposed in literature. For example, Wang and Chen (2011) indicate a series of revenue sources coming from ELVs recovery.

- High value (high demand), undamaged, recovered reusable components.
- High value secondary raw materials with high purity levels.
- Energy recovered and sold from incineration of the ASR's light fraction.

Basing on the EoL strategies, hierarchy, reuse and remanufacturing are preferable to recycling and energy recovery because they allow keeping a higher percentage of the embedded value already present in wasted products with a lower consumption of energy and natural resources (Kripli et al., 2010; Wang and Chen, 2012; Wang and Chen, 2013c). However, given the reduced amounts of reused and/or remanufactured parts (almost from 20% to 30% of cores follow this process (Ferrão and Amaral, 2006; Hiratsuka et al., 2014; Morselli et al., 2010)), recycling is one of the most common ways to recover materials and, even if in small percentage, the embedded value. In fact, the correct recycling of automotive electronic components could allow ATFs to improve their performances without increasing labour costs, and reducing disposal and plant's maintenance costs (Gerrard and Kandlikar, 2007; Tian and Chen, 2014). Furthermore, the reverse logistics flows could be optimised, by reducing transportation costs (Demirel et al., 2014). However, given a series of factors like (Clappier et al., 2014; Garcia et al., 2015; Schmid et al., 2013; Xu et al., 2014):

- wide amounts of ECUs models and alternatives;
- lack of precise data in literature;
- absence of specific regulations;
- inexistence of proper informatics decision-support tools,

An estimation of potential amounts of ECUs coming from ELVs (Vermeulen et al., 2011) and, subsequently, the amount of valuable resources potentially reusable as secondary raw materials, is not so simple to do.

## Discussion

In a world where the correct management of sustainable products and processes (and related lifecycles) is increasing in its importance, the automotive sector plays a relevant role. The European Union tried over the last two decades to develop a circular economy based on the exploitation of resources recovered by wastes (Cucchiella et al., 2015b). However, the previous literature review highlighted as current ELV directives, depending on weighted-based principles, do not adequately take into account the management of EoL automotive electronic components.

To this aim, the article offers interesting findings in technological, environmental and economic benefits that could be potentially achieved through the correct recycling of ECUs. In fact, their management could allow the reduction of both the quantity of wastes ending up in landfills and the use of additional resources during the production of new cars. This way, a considerable reduction of the overall automotive supply chain environmental impact could be reached. Furthermore, many new work positions could be opened, reducing the post-crisis effects on employment rates. Finally, all these benefits could be achieved with a very low political effort in terms of regulation changes.

However, the current vehicle recycling system technological level, together with the absence of a clear design for dismantling/recycling standards, does not easily comply with new recycling rates imposed by the EU ELV Directive for 2015 (95% by an average weight per vehicle and year as reference reuse and recovery rate, of which 10% coming from energy recovery of non-recyclable materials).

Over the years, many experts have found agreement in saying that the easiest way to improve current recycling rates is, from one side, to focus on a better management of the so-called ASR fraction and, from another side, to improve the dismantling phase performances by exploiting information communication technologies (ICTs) and databases. The article follows both these two visions, going to assess the embedded value in electronic components, a kind of systems that, especially in newest cars, seems to acquire even more importance in the management of all the vehicle's main functions. Currently, this kind of subcomponent (if not remanufactured) end directly in the ASR fraction, without any type of control. Instead, the literature confirms that their value is comparable with the one embedded in medium grade waste PCBs, present in many types of WEEEs (Birloaga et al., 2014). Given the increasing use of electronic subsystems in the automotive sector, the right management of these new types of e-wastes could represent a profitable business, both for automotive recyclers and car manufacturers.

Aiming to fulfil the gaps presented in the literature, a series of important studies should be implemented. First of all, the scientific literature focusing on EoL automotive electronics management should increase in number, trying to better present the issues from different views. For example, more focus on the potential profitability coming from the recovery of this type of e-waste would support the implementation of dedicated and flexible recovery centres (both mobile and field ones), where different types of automotive electronic components could be correctly managed in the same place (something similar was already studied for WEEEs (Cucchiella et al., 2015b)). In addition, profitability could be guaranteed also through a dedicated set of national laws (or changes in the current ELV Directive) and fees to be paid in case of noncompliance of correct EoL processes. In this direction, a quality-based (instead of a weight-based) policy on the recovery of resources should be followed. Also ICTs supporting the EoL decision-making process should be better integrated with the existing informative networks, already present inside a company. This need is evident in literature, where the non-cooperation between car manufacturers and OEMs and the rest of the reverse logistics chain is clear. Finally, some studies analysing possible issues arising from the recovery of materials from future ELVs are needed. For example, the dismantling process of lithium-ion batteries embedded into electric vehicles has already been considered by many authors as a primary issue to be solved before these cars will reach their EoL.

## Conclusions

ELVs are one of the most important sources of secondary raw materials. However, studies demonstrating the value embedded in their embedded electronic systems are quite rare. The absence of any kind of guidelines for the ECUs (the most valuable component among automotive electronic equipment) management in both ELVs and WEEEs Directives is a direct demonstration of this gap. Of course, ECU recycling would not contribute in a relevant way to reach the weighted-based recycling and recovery targets characterising current regulations, but would be very important under a critical raw materials recovery view.

The literature confirmed these assumptions about the environmental benefits related to the correct management of EoL automotive electronic systems. Furthermore, the economic assessment of the real value exploitable from ECUs has to be quantified for both single scraps, overall expected volumes and geographical distributions. Finally, flexible demanufacturing and recycling systems could allow better economies of scale and experience from a technological point of view. [AQ: 5]

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