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Review

A Structured Literature Review on Obsolete Electric Vehicles Management Practices

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Abstract: The use of electricity for transportation needs offers the chance to replace fossil fuels with greener energy sources. Potentially, coupling sustainable transports with Renewable Energies (RE) could reduce significantly both Greenhouse Gas (GHG) emissions and the dependency on oil imports. However, the expected growth rate of Electric Vehicles (EVs) could become also a potential risk for the environment if recycling processes will continue to function in the current way. To this aim, the paper reviews the international literature on obsolete EV management practices, by considering scientific works published from 2000 up to 2019. Results show that the experts have paid great attention to this topic, given both the critical and valuable materials embedded in EVs and their main components (especially traction batteries), by offering interesting potential profits, and identifying the most promising End-of-Life (EoL) strategy for recycling both in technological and environmental terms. However, the economics of EV recycling systems have not yet been well quantified. The intent of this work is to enhance the current literature gaps and to propose future research streams.

Keywords: obsolete electric vehicles; ELV management; circular economy; structured literature review

1. Introduction

The transportation sector is one of the main reasons for global warming. About one-third of the global energy demand and one-sixth of global Greenhouse Gas (GHG) emissions come from transport [1], mainly because of fossil fuels [2,3]. Given the increasing number of catastrophic events caused by climate changes, international institutions have decided to reconsider the way vehicles can move with a lower impact on the environment. Trying to answer to these trends, automotive manufacturers have been pushed towards the development of innovative technologies for the sustainable mobility of people and things [4,5], and this has also followed the circular economy concept [6,7]. Hence, Electric Vehicles (EVs) were developed under many forms, like BEVs (Battery Electric Vehicles), HEVs (Hybrid Electric Vehicles), PHEVs (Plug-in Hybrid Electric Vehicles), REEVs (Range Extended Electric Vehicles), FCEVs (Fuel Cell Electric Vehicles) and FCHEVs (Fuel Cell Hybrid Electric Vehicles). Each of them employs electricity in a different way in order to move [8,9]. Electric cars can be broadly classified into full electric and hybrid ones [10,11]. An EV moves only through an electric motor, whereas an HEV moves either with an electric motor or a conventional combustion motor. A battery stores the extra energy, by capturing it with regenerative braking systems. In a PHEV, the batteries can be loaded with additional grid electricity. In a REEV, either an internal combustion engine or the grid electricity charges the battery. A FCEV (or FCHEV) embeds a hydrogen tank and a fuel cell as a source of energy [12]. From a structural perspective, they can be considered a type of HEV, in which the fuel cell replaces the internal combustion engine. Using atmospheric oxygen and compressed gaseous hydrogen supplied from the on-board tank, the fuel cell generates electricity, which powers the vehicle's electric motor [13].

According to the Global EV Outlook of the Electric Vehicle Initiative (EVI) and the International Energy Association (IEA), the global EVs exceeded 5.1 million in 2018, up 2 million from the previous year. China is the world's largest electric car market with 2.3 million units, followed by Europe (1.2 million units) and the USA (1.1 million units). This outlook defines the future global electric car sales in 2030 by considering two potential scenarios: 23 million units in the New Policies Scenario and 43 million units in the EV30@30 Scenario (Figure 1) [10].

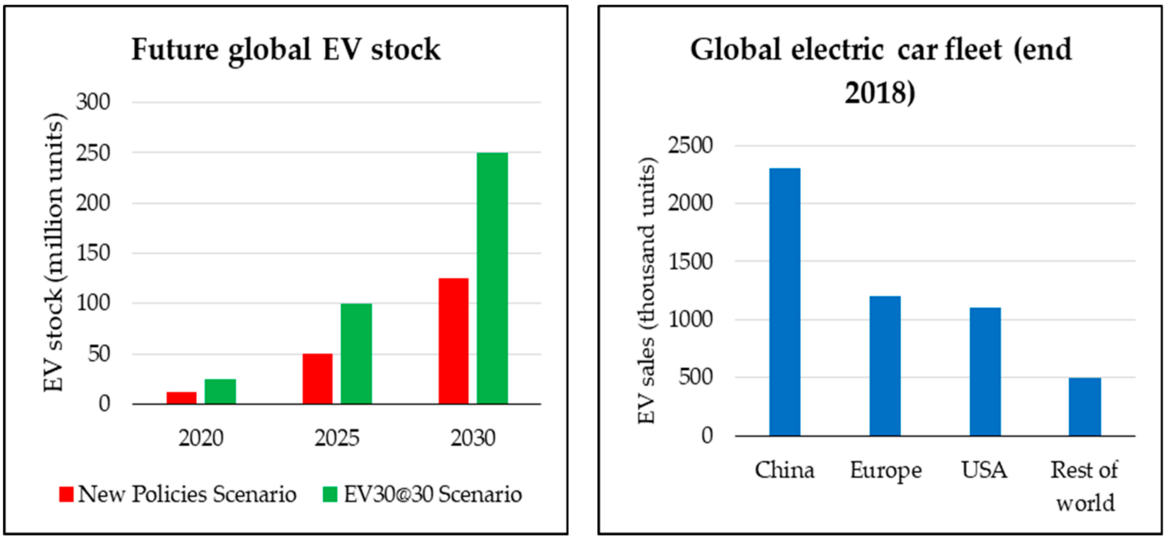

Figure 1. Global EV stock in 2020–2030 period and global EV sales in 2018 [10].

Several studies already assessed the higher sustainability of EVs compared with common Internal Combustion Engine Vehicles (ICEVs) [14–16]. However, EVs are not immune from criticism. Generally, their weight is higher than ICEVs (because of batteries, electric motors, power electronics, etc.), their range of action is limited and recharging infrastructures are lacking [11,17,18]. Furthermore, one of the most important issues related to EVs is that, given their higher complexity, they are very difficult to recycle [19–24]. In order to summarize the available knowledge and provide evidence for the main gaps that are still waiting for innovative answers, a structured literature review is proposed in this work.

The paper is organized as follows. Section 2 presents the topic conceptualization and classification, describes the research methodology and assesses the framework of analysis. Section 3 shows the literature review metrics adopted and proposes an overall view on results. Section 4 shows a discussion on the relevant topics analyzed by proposing a critical perspective. Finally, Section 5 presents some concluding remarks.

2. Materials and Methods

2.1. Topic Conceptualization and Classification

Renewable Energies (REs), sustainable transportation and waste management strategies have assumed a central role in the last decades, not only in theoretical terms, but also in practice [25,26]. Citizens, firms and governments are extremely interested in creating economic opportunities and preserving the environment. Their combination could potentially reduce the environmental impact of every human activity and offers interesting chances for new businesses [27]. Among waste management strategies, there is great attention paid towards recycling [28–31]. An assessment of the knowledge on EVs gives us the chance to put together all these points.

2.2. Research Methodology and Framework of Analysis

In order to assess the whole knowledge on EVs, a systematic literature review was implemented. After a deep survey, a list of papers selected through the most popular scientific works search engines (e.g., Google ™ Scholar, Web of Science ™, Sage ™, Science Direct ™, Springer ™, MDPI ™, Emerald ™, Scopus ™, Taylor & Francis ™ Online and Wiley ™ Online Libraries) have been evaluated [32]. All of the selected scientific documents have been published between 2000 and 2019. They have been provided by adopting a series of combinations of two keywords like "recycling" and "electric vehicle" that have been researched in the titles, abstracts and keywords of papers. After a deep reading of all the papers, a structured literature review was performed, and the main results are summarized below. The output of the searching process in terms of number of works published by year is proposed in Figure 2. The number of total documents (n° 171) reveals the considerable attention devoted to these topics, especially from 2015 onwards, with about 67% of documents concentrated between 2015 and 2019. Documents pertain to n° 100 scientific journals with impact factor, n° 27 scientific journals without impact factor, n° 28 proceedings of scientific conferences, n° 10 scientific reports, n° 4 industrial reports and n° 2 book chapters.

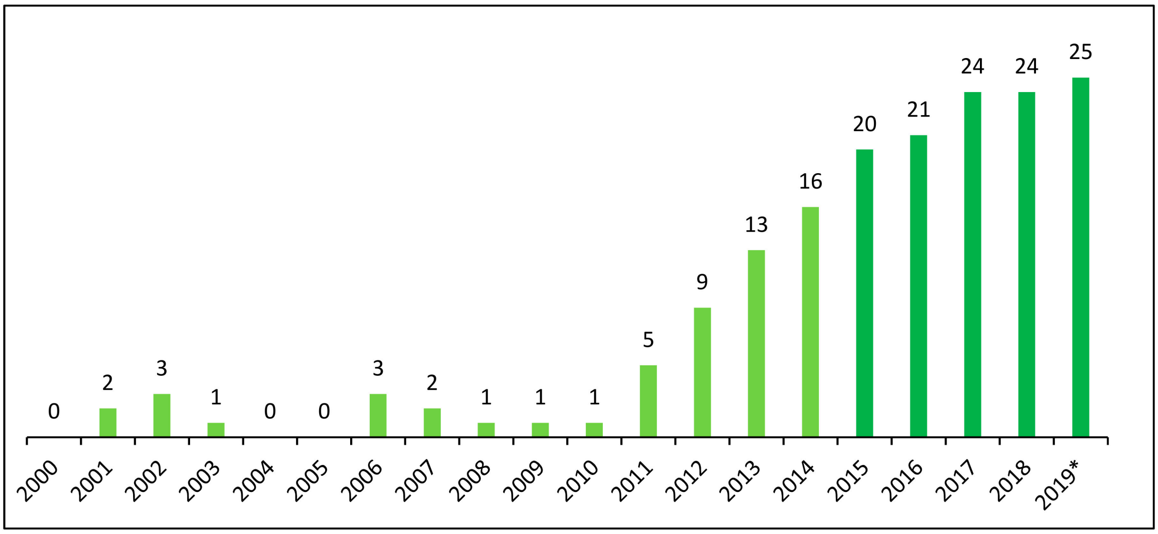

Figure 2. Historical series of published papers from 2000 up to 2019 (partial).

The growth trend reached its peak during the last year examined. The 2019 data are partial, but greater than the previous years. The last available data speak about a new record of EVs on the road, with a global EV stock of about 5.1 million vehicles in 2018, up 2 million from the previous year [10].

Figure 3 displays the geographical distribution of documents, where the institution of the first author was considered as reference. This distribution is concentrated in China, the USA and Germany. These countries cover about 50% of the total number of published articles.

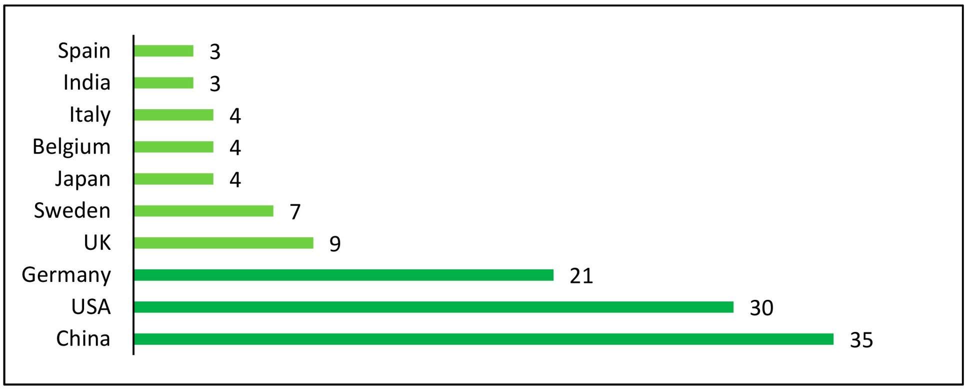

Figure 3. Geographical distribution of published papers.

China occupies the first position with n° 35 documents, followed by the USA with 30 documents, coinciding with their role in the automotive market. In fact, China was the global leader in EV manufacturing from 2016 onwards [33–35], while the USA occupied this role till 2015 [36]. Interestingly, Germany has a lower stock of EVs than other countries, but a high relevance in the European automotive sector and has a high involvement of the government towards the research and diffusion of EVs [37]. There are several perspectives from which EVs and recycling were addressed by the literature (Figure 4) [38]. In macroscopic terms, the EV End-of-Life (EoL) strategy is the most discussed topic. Among these strategies, recycling is the best solution (n° 52 documents). The second most discussed topic is the environmental evaluation of EVs (n° 40 documents), performed to underline the advantages of moving towards sustainable goals [39], while the economic and social benefits of EV recycling are not well assessed by the experts. In addition, several authors dedicated great attention to a specific EV component (batteries) [40].

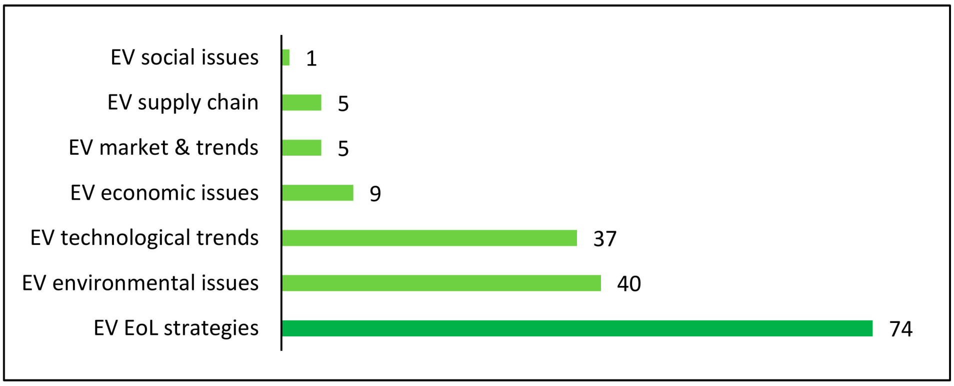

Figure 4. Macro topics of published papers.

The analysis of macro topics highlights that research on EVs follow a multidisciplinary strategy. About the research methodology, it is broadly based on the analytical approach (n° 129 documents). Theoretical, survey and case studies are very limited, with 37, 3 and 2 documents, respectively. In the following section, each macro topic is discussed in detail.

3. Results

The structured literature review showed that articles pertaining to the obsolete EV management practices could be classified in three types:

- Works on EV disassembly (see Section 3.1);
- Works on EV recycling (and reuse, just for batteries)—(see Section 3.2);
- Works on EV remanufacturing (see Section 3.3).

In addition, considering only EV recycling, the three pillars of sustainability are explored as well:

- Works on EV recycling environmental issues (see Section 3.4);
- Works on EV recycling economic issues (see Section 3.5);
- Works on EV recycling social issues (see Section 3.6).

3.1. EV Disassembly

When considering a traditional ELV dismantling process, disassembly is the second activity, after fluids and hazardous systems decontamination, done by car dismantlers on obsolete vehicles. It represents a high value stage for car dismantlers, given that disassembled components (if in good conditions) can usually be resold as spare parts on the secondary market. For EV disassembly, the main elements taken into account by experts are batteries, electric engines and power electronics (see Table 1).

Table 1. Focus of EV disassembly-oriented papers.

Author	Battery	Engine	Electronics
[41]	x		
[42]	x		
[43]		x	
[44]			x
[45]			x

For the batteries, disassembly is done (after discharging) immediately before either recycling or remanufacturing. Given the lack of information in product variants, battery disassembly is done manually. Only two examples have been found in literature [41,42]. Here, the authors present a concept for a battery disassembly workstation where operators are assisted by robots. While persons perform more complex tasks, robots perform simple and repetitive tasks, such as removing screws and bolts from cases. A similar approach is proposed also by [43], but focusing on EV electric engines.

Finally, other experts focus on power electronics [44,45]. Here, a robotized workstation is proposed for the automatic disassembly of electronic components from EV batteries before their final recycling. An identification of the profitability of recycling such electronic components is also provided.

One of the first steps of EoL management is disassembly, typically requiring several time/cost consuming processes. It depends on the costs and risks related to the ability to separate the sub-components from the whole product as to whether disassembly is viable or not. From a technological point of view, manual procedures are usually adopted, explaining the low number of papers focusing on this topic.

3.2. EV Recycling

The EVs market is one of the most interesting fields from the recycling point of view. A generic EV embeds lots of key materials (almost 25 kg per car) inside different subsystems and components, offering great recycling potentials. Some important examples are represented by traction batteries, electric drive motors and power electronics [46]. The production of electric cars is expected to grow rapidly, reaching 20 million cars by 2020 [36]. By assuming a mean life of a car of 10 years, there will be an enormous amount of EVs to be recycled by 2030. From these data, it is clear that the strategic importance can be assumed by a preventive decision about alternative sustainable treatments for this waste flow. In particular, the use of industrial symbiosis can minimize material wastage and environmental burdens [23]. A comparison among recycling methods is proposed by some authors [47], in which the final result defines the role of recycling policies that aim to incentivize battery collection and emissions reductions (Table 2).

Table 2. Focus of EV recycling-oriented papers.

Author	Battery (Reuse/Recycle)	Magnets	Electronics	Fuel Cells
[48]	x			
[49]	x			
[50]	x			
[51]	x			
[52]	x			
[53]	x			
[54]	x			
[55]	x			
[18]	x			
[42]	x			
[56]	x			
[57]	x			
[21]	x			
[58]	x			
[50]	x			
[59]	x			
[60]	x			
[61]	x			
[62]	x			
[63]	x			
[64]	x			
[65]	x			
[66]	x			
[67]	x			
[68]	x			
[69]	x			
[70]	x			
[71]	x			
[72]	x			
[73]	x			
[42]	x			
[74]	x			
[75]		x		
[76]		x		
[77]		x		
[78]		x		
[79]		x		
[80]		x		
[46]			x	
[81]			x	
[82]				x
[13]				x

Recycling is an opportunity to close the loop of EVs, which aims to reach sustainability goals. However, specific recycling pillars are proposed in the next sub-sections. One of the main results from this review is the significant number of papers focusing on this EoL option. Certainly, reuse is a better solution in terms of the waste hierarchy, but it is not always feasible from a technical point of view. Recycling processes, instead, are suitable to satisfy the circular economy model. Material circularity requires the development of secondary markets where critical and special metals can re-enter in the raw materials cycle. As the authors express, in order to support this development, the economic side must be always taken into account when new technological options are selected.

3.2.1. EV Battery Recycling

The EoL management of EV batteries is one of the most discussed issues in literature. Broadly speaking, EoL strategies can be distinguished in three categories: reuse, remanufacturing and recycling. Literature works are focused on the pros and cons related to each battery technology from both technical, environmental and economic perspective [83–86]. Other authors focus on both a kind of technology (usually Li-ion) and the management of materials embedded in batteries [87–90] (Tables 3–5). Considering the economic perspective, the cost of EV batteries plays a critical role in determining the commercial viability of EVs, not only during their usage, but also at the end of their useful life. Spent batteries maintain a relevant market value as manufacturers can extract critical materials from key components (e.g., cells and power electronics), typically through hydrometallurgical processes. This topic is investigated from multiple perspectives in literature (see Table 2).

Table 3. Focus of EV battery reuse-oriented papers.

Author	Environmental	Economic	Technical
[48]	x		
[49]		x	
[50]		x	
[51]		x	
[52]			x
[53]			x

Table 4. Focus of EV battery recycling-oriented papers.

Author	Current State	Predictions	Technologies
[54]	x		
[55]	x		
[18]	x		
[42]	x		
[56]		x	
[57]		x	
[21]		x	
[58]		x	
[50]		x	
[59]			x
[60]			x
[61]			x
[62]			x
[63]			x
[64]			x
[65]			x
[66]			x
[67]			x
[68]			x
[69]			x
[70]			x
[71]			x
[72]			x
[73]			x
[42]			x
[74]			x

Table 5. Technologies supporting EV battery recycling processes.

Author	Hydrometallurgy	Biometallurgy	Mechanical	Mixed
[59]	x			
[60]	x			
[61]	x			
[62]	x			
[63]	x			
[64]	x			
[65]	x			
[66]	x			
[67]	x			
[68]	x			
[69]	x			
[70]		x		
[71]		x		
[72]			x	
[73]			x	
[42]				x
[74]				x

One way to manage obsolete EV batteries is represented by reuse. Given the short lifetime of an EV battery (quantified by many experts as 8–10 years—or the period where the battery capacity reduces to 80% of the original one), their reuse is seen by experts as a reasonable and sustainable strategy, before opting to recycle [48]. Better performances can be obtained by reusing EV batteries together with Renewable Energy (RE) sources in stationary applications. Because of this, several business perspective are proposed in the literature, either under the form of Product-Service Systems (PSSs) [49], dedicated EU regulations [50] or are considered industrial symbiosis [51]. However, the most effective way to manage obsolete EV batteries seems to be a combination of both reuse and recycling practices [52,53].

Several papers have been written about EV battery recycling in the last decades. In general terms, EV battery recycling follows the same process exploited for recovering any type of e-waste, with disassembly, shredding, separation and refining as the main process steps. Depending on the technologies employed during refining (chemical or mechanical ones), it is possible to reach different material recovery performances.

From the current state of the art perspective on EV battery recycling, some works are available in literature, but none of them consider this topic in a broad perspective. Some experts focus on the EV battery design stage by considering the economic and environmental strategies supporting the sustainable treatment of these products [54]. Others follow the same logic, but focus on either a specific type of EV battery [55], national context [18] or recycling method [42].

From the prediction perspective, the focus is on critical materials embedded into EV batteries, either in terms of current availabilities, projected mining capacity or forecasted demands [56]. These assessments are usually presented under the form of decision-support tools [57] or generic simulation platforms [21]. Finally, other experts assess the introduction of EV batteries recycling on current ELV regulations by taking as reference either the Umicore battery recycling process [58] or the Chinese context [50].

From a technological perspective, EV battery recycling is a well-assessed topic in literature, with a prevalent role for the hydrometallurgical process, given its high performances in terms of materials recovery. Some authors describe it through a review on the evolution of chemical recovery technologies [59,60]. Others prefer to focus on either a specific chemical process [61,69], separation processes [66–68], EV battery type [62], leaching agent [63] or recovered material [64,65]. A promising sub-category of hydrometallurgical processes is represented by biological ones. However, only two works have been found in literature on this topic, and both of them focus on organic leaching agents [70,71]. The mechanical process is another way to recover EV batteries. However, in this case, only two works have been found in literature [72,73]. Finally, other experts put together both chemical and mechanical processes, by employing all their benefits [42,74].

3.2.2. EV Magnet Recycling

After EV batteries, EV magnets are the second element discussed in literature. Several works present innovative ways to recover Rare Earth Elements (REEs) from obsolete magnets, either coming from mixed sources [75] or specific waste streams (including magnets from HEVs) [76–78]. Other works quantify present and future amounts of recovered REEs from specific HEV components [79]. Finally, different recycling approaches for recycling magnets from HEVs are compared [80].

3.2.3. EV Power Electronics Recycling

As evidenced by the authors many times for common ELVs, in the similar case of EVs, the recovery of electronic components is still in its infancy [46]. Even if electronics in EVs are even more present than in ICEVs, neither industry, nor politics, nor scientists consider its recovery to be an important issue, preferring to focus on batteries (see the previous Sections 3.2 and 3.2.1). The only paper found in literature on this topic compares, both in economic and environmental impact terms, two different ways to recycle EV power electronics, by exploiting either traditional ELV recovery processes or coupling them to a dedicated plant [81].

3.2.4. Fuel Cells Recycling

Another focus related to EVs is the recycling of fuel cells. Given the difficulty of the BEV's ability to cover long distances, FCEVs will surely take part of the market in future car sales. This way, a percentage of future obsolete EVs will be constituted by FCEVs. Unfortunately, also in this case, only two articles have been found in literature. The first one assesses the effects of a probable update of the current EU ELV Directive towards the recovery of fuel cells [82]. The second one investigates the potential contribution offered by the recycling of FCEVs for meeting the current platinum demand of Europe [13].

3.3. EV Remanufacturing

The remanufacturing of components coming from obsolete cars is a well-assessed business. However, from an EV perspective, the literature considers of only EV battery remanufacturing. Considering the few papers focusing on that, EV battery remanufacturing is discussed in terms of either overall process [91], economic performances (compared with reuse/recycling ones) [92,93] or real application cases [94].

3.4. EV Environmental Issues

The diffusion of EV technologies is strictly related with energy storage technologies [95]. This way, the environmental analysis has been historically focused on the use phase of EVs. However, many components of EVs (e.g., electronics, magnets and batteries) embed critical raw materials. In this way, experts have started to assess the positive environmental impact associated with EV recycling (as a more sustainable alternative than landfilling), both in terms of GHG emissions reduction [20], electricity mix generation technologies [96], secondary resources recovery (specifically REEs [97], critical metals [12] and lithium [98]) and policy measures that ensure the availability of materials [33].

3.5. EV Economic Issues

An important result coming from the present work is that economic issues of EV recycling systems are not well assessed. In particular, the following gaps have been evidenced [99]:

- Scarcity of studies assessing the potential value of different EV battery technologies [100,101];
- Low EV battery recycling rates given the focus of recycling plants on high-volumes [102];
- Translation of expected environmental benefits into real economic benefits [103].

3.6. EV Social Issues

Social issues related with EVs are rarely assessed by the experts, mainly in terms of the social influence on eco-innovation adoption. For this topic, just one paper [104] underlined the importance of interpersonal social influence, opinion leadership and personal norms on eco-innovation adoption.

4. Discussion

Satisfying human needs in the most sustainable way (and without further impacting the climate) is the greatest challenge of the 21st century. The experts demonstrated in several works that both renewable energies and waste management strategies (either individually or together) can guarantee improvements in this sense [105–107]. Obsolete EV management practices represent a good example because several types of data (e.g., EV configurations, battery energy sources, electrical machines, charging systems, optimization techniques) are required [108,109].

From one side, EVs represent the answer of car manufacturers towards international directives that, for decades, have been asking for greener and more sustainable vehicles [34,110,111]. Hence, their reuse, remanufacturing and recycling is considered by many authors as a potential solution to several environmental challenges, like resource scarcity, sustainable economic growth and waste management [112,113]. From this side, some quantitative analyses are available [114,115]. However, given the great uncertainty related with either global volumes (see Table 1 for details), growth rates and the general evolution of the EV market, it is very difficult to have reliable estimates, even by adopting the most advanced simulation tools [116,117]. Therefore, none of the most recent works on ELVs investigate how EVs could influence future ELV trends. These data are of utmost importance not only for car manufacturers, but also for policymakers [118]. Based on these data, industries (especially those involved at EoL stage) could decide how to improve their plants' recovery performances, especially for low-volume materials. Instead, politicians could monitor illegal ELV flows and sustain the EV market expansion through optimized subsidy policies.

From a second perspective, the management of EV components (e.g., batteries, electric motors and electronic components) presents some knowledge gaps. The literature is full of articles considering batteries and electric motors to be promising components worth recycling [119]. However, power electronics could also increase the overall profitability, but few works assessed and quantified it [120,121]. This way, current recycling technologies must be improved if companies involved in ELV reverse logistic chains are willing to gather the highest profit from EVs [122–125]. Contrarily, the risk is the same encountered by companies when managing electronic components of ICEVs. Also, this change will be needed in terms of a legislative re-thinking of current regulations and procedures, by offering a concrete support to actors willing to enter into current ELV recovery chains [126]. Here, innovative directives, environmental requirements and technologies able to manage obsolete EVs are urgently needed [127].

From a third perspective, recycled metals represent the most interesting source of both economic and environmental benefits, given the huge amounts embedded in EVs. However, limiting the recycling process to cathode materials will play a negative effect on the EV battery recycling economics and the environmental impact [128]. This way, neither reward-penalty mechanisms nor subsidy policies will be sufficient [129]. The only way to increase profitability will be to consider the most valuable elements embedded in EVs, like power electronics and magnets.

Results coming from the work underlined, like the adoption of new technologies, can increase the efficiency and effectiveness of entire recycling processes towards more sustainable practices. At the same time, economic aspects related to recycling processes seem to not be well analyzed by the literature, and the main variables affecting their profitability are not well understood. These elements, together with the break-even point expressed in terms of the number of ELVs recycled per year, represent some interesting research areas for the future.

5. Conclusions

Currently, automotive manufacturers are investing big amounts of money on EVs, and the market is characterized by big growth trends and economic opportunities. However, environmental advantages could be obtained only if EVs can be really green, either in terms of the type of energy source exploited (i.e., powered by RE sources) or by considering different EoL strategies and by following the circular economy paradigm. From this last perspective, the current work shows lots of papers studying new ways to recycle EVs. Some of them are focused on the disassembly of whole cars, some on reuse of the components, some on reverse logistic chains and others on remanufacturing of components. However, lots of experts focus on EV battery recycling, especially Li-ion ones. Given their weight and content in critical materials, a battery is considered to be one of the prevalent elements to recover from EVs. However, we think that EVs can present other interesting components that are worth recycling, usually not considered by both scientific and industrial experts.

In order to avoid what currently happens during the recycling of ICEVs, the present paper wanted to assess the existing literature on EV recycling, trying to evidence current lacks in knowledge and to open issues for potential improvements. They can be summarized in: (i) limited estimates of future ELV streams, (ii) limited assessment of relations among stakeholders within the reverse logistic chain, (iii) limited studies on economic issues, (iv) absence of social analyses and (v) limited case studies considering the three sustainability pillars together.

Results highlight six considerations: (i) the topic is multidisciplinary and actual; (ii) economic evaluation is needed to develop the ELV recycling sector; (iii) the role of power electronics is not investigated into detail; (iv) the applicability of Circular Economy (CE) models on ELVs is feasible; (v) the pivotal role of recycling activities within CE models is verified and (vi) both waste management and renewable energy management can support the development of sustainable activities.

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Acronyms

BEV	Battery Electric Vehicle	GHG	Greenhouse Gas
CE	Circular Economy	HEV	Hybrid Electric Vehicle
ELV	End of Life Vehicles	ICEV	Internal Combustion Engine Vehicle
EoL	End of Life	IEA	International Energy Association
ESS	Energy Storage System	LIB	Lithium Ion Battery
EU	European Union	PCB	Printed Circuit Board
EV	Electric Vehicle	PHEV	Plug-in Hybrid Electric Vehicle
EVI	Electric Vehicle Initiative	RE	Renewable Energy
FCEV	Fuel Cell Electric Vehicle	REE	Rare Earth Elements
FCHEV	Fuel Cell Hybrid Electric Vehicle	REEV	Range Extended Electric Vehicle

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