

Article

Economic Sustainability of Scrapping Electric and Internal Combustion Vehicles: A Comparative Multiple Italian Case Study

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Abstract: The transition to sustainable mobility is one of the most pressing and complex challenges for the automotive industry, with impacts that extend beyond the mere reduction of emissions. Electric vehicles, while at the center of this evolution, raise questions about the consumption of natural resources, such as lithium, copper, and cobalt, and their long-term sustainability. In addition, the introduction of advanced technologies, including artificial intelligence (AI) and autonomous systems, brings new challenges related to the management of components and materials needed for their production, creating a significant impact on supply chains. The growing demand for electric and autonomous vehicles is pushing the industry to rethink production models, favoring the adoption of circular economy principles to minimize waste and optimize the use of resources. To better understand the implications of this transition, this study adopts a multiple case study methodology, which allows in-depth exploration of different contexts and scenarios, and analysis of real cases of dismantling and recycling of internal combustion engines (ICEs) and electric vehicles (EVs). The research includes a financial simulation and a comparison of revenues from the dismantling of ICE and EV vehicles, highlighting differences in the value of recycled materials and the effectiveness of circular economy practices applied to the two types of vehicles. This approach provides a detailed overview of the economic benefits and challenges related to the management of the end of life of vehicles, helping to outline optimal strategies for a sustainable and cost-effective future in the automotive sector.

Keywords: electric vehicles (EVs); ICE vehicles; end-of-life (EOL); EV battery recycling; scrapped vehicle management; scrapping process; material recovery; economic comparison ICE vs. EV



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1. Introduction

Research on global automotive production and purchasing indicates that approximately 78 million new cars were produced in 2020, down by about 15% from the forecast. This decline was mainly caused by the economic recession due to the COVID-19 pandemic [1]. Despite these uncertainties, the International Organization of Motor Vehicle Manufacturers (OICA) predicts that, compared to the 1.28 billion vehicles in use worldwide in 2015, by 2040, the share of new electric cars sold will reach about 54%, with internal combustion engines accounting for the remaining 46% [1,2].

Fossil fuel shortages, climate change, and technological advances in batteries, fuel cells, electric motors, and power electronics have led to a growing interest in low- and zero-emission vehicles. Hybrid (HEV), plug-in hybrid (PHEV), fuel cell electric (FCEV),

and pure electric (EV) vehicles have become protagonists of more sustainable mobility solutions [2]. However, this technological shift has generated new challenges related to the use of innovative components and materials that require a rethinking of the recycling processes of end-of-life vehicles [3,4].

2. Background

The automotive sector is one of the most influential industrial sectors in terms of environmental, social, and economic impacts. On the one hand, automotive technologies are rapidly advancing, with a progressive shift toward more sustainable vehicles, such as hybrid, plug-in, fuel cell, and electric vehicles. These vehicles represent promising solutions to address issues related to environmental pollution and the exploitation of natural resources but also economic and social challenges [4,5].

However, the introduction of these new mobility solutions has also generated new challenges related to the use of innovative components and materials that cannot be ignored and that must be effectively integrated into vehicle recycling processes [4]. Electric vehicle batteries, advanced propulsion systems, and composite materials used in modern vehicles pose significant challenges in terms of their disposal and recycling [6]. These challenges are amplified by the need to develop an adequate recycling infrastructure that can handle new materials and components, while preserving the environment and reducing the overall ecological impact [7]. The shift to sustainable mobility solutions implies not only a change in propulsion technologies but also a profound transformation in the management of materials and resources. New technological components, such as lithium-ion batteries, require disposal and recycling solutions that are not yet fully developed and, at the same time, the automotive sector faces an increasing demand for scarce resources, which fuels concerns about their supply and environmental impacts [8]. The ecological challenges that the automotive sector must address are linked to global environmental issues, such as climate change, biodiversity integrity, ocean acidification, biogeochemical fluxes of nitrogen and phosphorus, freshwater use, land use, and the release of new chemicals. These factors, known as “planetary boundaries” [9,10], represent the limits within which human activity should remain to ensure global sustainability. Added to these problems are reduction of the ozone layer and air pollution from aerosols, which are also crucial issues for the sustainability of the sector.

2.1. Challenges of the Automotive Sector

The automotive sector is one of the most relevant industries for the European Union economy [11]. However, the transition toward more circular models is having a significant impact on the main related industries, which exploit complex supply chains and face challenges related to shortages of semiconductors and skilled labour. The need to adopt the concept of a circular economy (CE) has become crucial for the sector as it is key to achieving the climate neutrality objectives set by the European Green Deal by 2050 [12]. This initiative promotes Sustainable Development Goals (SDGs), in particular, SDG 9 “Industry, Innovation and Infrastructure”, SDG 12 “Responsible Consumption and Production”, and SDG 13 “Climate Action”, in order to address the following issues [13]:

1. The design and production of vehicles that contribute sufficiently to the development of a climate-neutral, clean, and circular economy (‘design and production’ issue area);
2. The treatment of vehicles at the end of their life cycle is not optimal with respect to its potential to contribute to a climate-neutral, clean, and circular economy (‘waste treatment’ issue area);

3. A significant share of vehicles subject to the End-of-Life Vehicles Directive are not collected for good environmental treatment in the EU, contributing to pollution in third countries ('collection' issue area);
4. The lack of a level playing field at the EU level for the design, production, and end-of-life treatment of vehicles detracts from the circular economy objectives of the European Green Deal ('scope' issue area).

The main goal of the automotive and industrial sectors is to reduce emissions and reach the "zero emissions" target [14]. In this direction, the electrification of transport is considered one of the key solutions as it presents itself as an environmentally friendly and sustainable technology [15]. However, despite benefits in terms of emission reduction, electrification also involves three key challenges [1]:

- Reduction of the consumption of combustible resources [10];
- The demand for new vehicles will produce huge quantities of end-of-life vehicles (ELVs) waiting for adequate treatment [1];
- The spread of cars equipped with modern technologies, such as artificial intelligence, autonomous systems, and energy-saving electric batteries, requires new production and disposal strategies [4].

The shift toward electric vehicles as the future of sustainable mobility presents a dilemma related to the concept of green growth. While the spread of electric vehicles can reduce emissions, it also puts increasing pressure on natural resources, such as lithium, copper, and cobalt, which are needed for battery production [16]. The intensive use of resources for battery production makes it difficult to pursue green growth as there is no concrete evidence that linear economic growth can be separated from environmental pressures [6]. Therefore, it is essential to review the development model and consider the global impact that the automotive industry has on the environment, going beyond the limited perspective of emissions alone [17].

2.2. Summary of the Regulatory Context

The automotive sector is strongly influenced by environmental legislation and European policies that aim to ensure sustainability and reduce the environmental impact of its activities. At a European level, regulations focus on various aspects, including the management of end-of-life vehicles, vehicle type approval, and battery regulation.

Directive 2000/53/EC establishes requirements for the management of end-of-life vehicles, requiring that a significant proportion of vehicles at the end of their life be treated and recycled efficiently, minimizing their environmental impact [18,19]. The directive sets targets for the recovery and recycling of vehicle components, including hazardous materials and chemicals, to promote a circular economy in the automotive sector. Furthermore, it establishes the obligation for manufacturers to design vehicles that are easily disassembled and recyclable, encouraging the use of recycled materials [13]. The directive initially envisaged a recycling rate of 80% and a recovery rate of 85% by the beginning of 2006; starting from 2015, the target rates were increased to 85% for recycling and 95% for recovery [1].

Another key issue for the automotive sector concerns the regulation of batteries, especially those used in electric vehicles. Batteries are a crucial component for the electrification of transport, but their production and disposal raise important environmental and safety issues. As we see in Table 1, Directive 2006/66/EC imposes obligations for the collection, recycling, and management of batteries at the end of their life, with the aim of reducing environmental impact and promoting the reuse of materials [20,21].

Table 1. Targets for battery recycling of the 2020 EC proposal; data from [20].

Targets	Year	Cobalt	Copper	Lead	Lithium	Nickel
Minimum recycled content in new batteries	2030	12%	NA	85%	4%	4%
	2035	20%	NA	85%	10%	12%
Recovery rate from scrapped batteries	2026	90%	90%	90%	35%	90%
	2030	95%	95%	90%	70%	95%

The introduction of electric vehicles also involves the adoption of 3R (Reduce, Reuse, Recycle) approval standards, which oblige manufacturers to design vehicles with greater attention to the recyclability and reuse of components, as well as to improve end-of-life treatment strategies [13].

Finally, European legislation is evolving to promote more circular business models. Strategies such as Extended Producer Responsibility (EPR) are emerging, which is an approach to environmental policies in which the producer's responsibility for a product is extended to the post-consumer stage of the product's life cycle. In particular, EPR policy [22] is characterised by the transfer of responsibility (physical and/or economic; total or partial) upstream to the producer and away from municipalities; and the provision of incentives to producers to take environmental considerations into account in the design of their products. While policy instruments tend to focus on a single point in the chain, EPR seeks to integrate signals from the environment with product characteristics and production processes along the entire product chain [22].

3. Materials and Methods

Case study research is an in-depth and detailed analysis of a specific event, situation, organization, or social unit. Each case is characterized by having well-defined boundaries in terms of space and time, representing “a phenomenon within a delimited context”. This methodology is particularly suitable for investigating contemporary phenomena in their real-life context, where the context itself plays a significant role. When the boundaries between phenomenon and context are not easily distinguishable, the case study uses multiple sources of data to build a solid and verifiable framework. This approach ensures an integrated vision, combining different perspectives for a richer and more complete understanding of the phenomenon studied [23].

Multiple case study methodology is a research strategy that involves the systematic analysis of multiple cases within a single study. This methodology is often used in the social sciences to explore complex phenomena, identify patterns, and understand the different variables that influence a given context. Multiple case study methodology is particularly useful for delving deeper into a question or problem, providing a broader and more detailed perspective [24]. A multiple case study involves the selection and analysis of multiple cases, which can be individuals, organizations, events, or other entities, within a single research study. Each case can be considered as a “unit” of study, and the overall analysis aims to identify similarities, differences, patterns, and trends among the various cases. The main goal is to provide an in-depth analysis of the phenomenon being studied and to build a broader understanding of the context in which it occurs [25,26].

In our research, multiple case study methodology is suitable because it allows us to directly compare specific models of internal combustion engine vehicles with electric ones. This type of comparison helps to clarify differences in terms of the value of spare parts and scrap, as well as highlight issues related to the management of the traction battery, which is a crucial aspect for electric vehicles. With a multiple case study, we can explore in detail the economic and environmental factors that influence the value and sustainability of recycling, such as battery disposal costs, revenues from the sale of spare parts, and environmental

benefits. This allows a more complete assessment of the benefits and challenges of the transition to electric vehicles [27].

Financial Simulation

To reflect the economic as well as scientific and environmental benefits of electric vehicle recycling practices, a conceptual economic model, adapted from [28], and reported in Figure 1, has been considered.

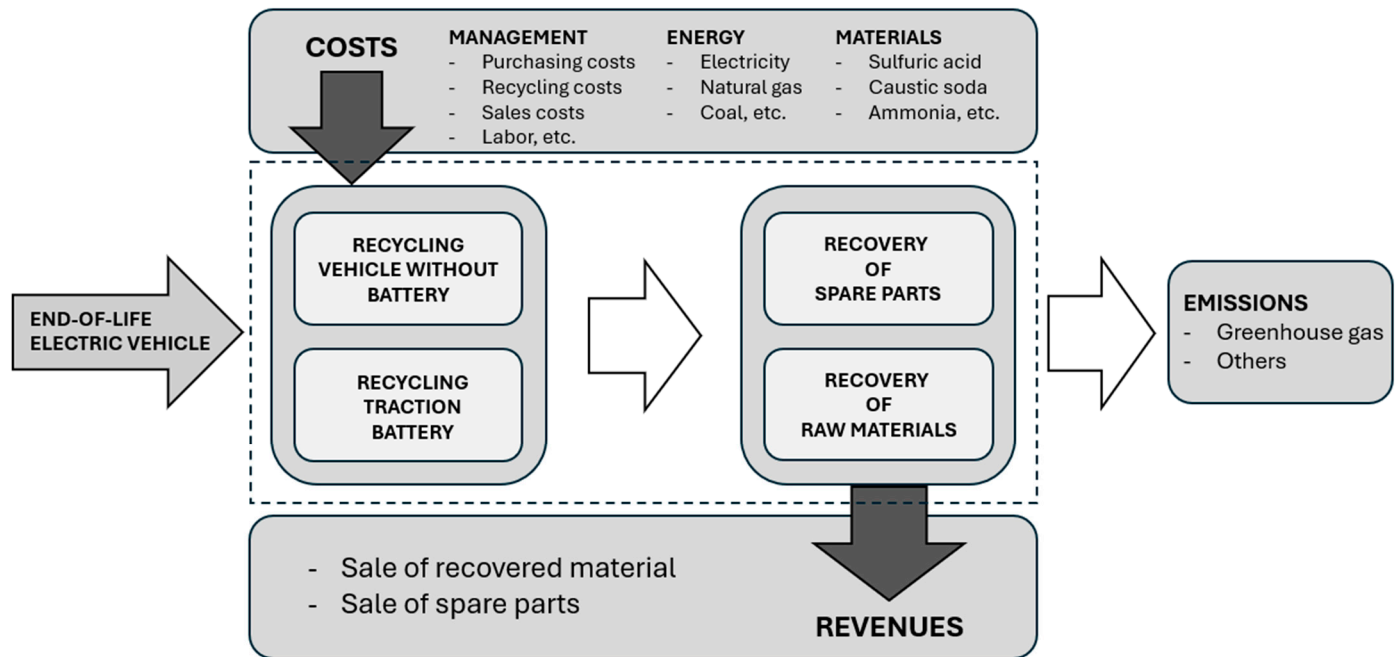


Figure 1. Conceptual economic model of electric vehicle recycling, adapted from [28].

The model considers all the main factors that influence the revenues and costs of the process. In particular, the model includes the following:

- The cost of purchasing the electric vehicle;
- The costs associated with the entire recycling process,
- The disassembly and treatment of components (dashed box);
- Revenues from the sale of second-hand products obtained from the process;
- The recovery and sale of scrap metal, with a focus on both the economic and environmental benefits of reusing materials.

Some of the indicators described in the model will not be considered in the analysis as they are irrelevant for the economic comparison of the demolition proceeds; in fact, the purchase costs are approximately the same depending on the vehicle categories. Furthermore, it is important to note that our study does not consider the fixed costs associated with the adoption of new recycling technologies and devices, nor the greenhouse gas emissions related to the entire life cycle of the process. These costs will in fact be diluted with the increase in operational capacity and the optimization of technologies. Since the objective of the study is to compare the economic and environmental benefits in a consolidated recycling process context, the barrier to entry for new entities is not considered. As a result, the economic and environmental benefits presented will be higher than the initial estimates, offering a more optimistic picture of future scenarios.

4. Results

This chapter analyzes the economic value resulting from the scrapping of internal combustion engine (ICE) and electric vehicles (EVs) through three different analyses: sale of spare parts, sale of scrap, and a comparison between vehicles belonging to the same market segment.

4.1. Spare Parts Sales

The analysis compares the economic value of saleable spare parts resulting from the scrapping of a Fiat 500 with an internal combustion engine (ICE) and an electric one (EV). The Fiat 500 was chosen as the focus of this study because, at the time the study was conducted, it was one of the most popular cars in Italy. Additionally, it presents the unique advantage of having two identical versions differing only in their powertrain, making it ideal for a direct comparison.

Table 2 compares the characteristics and economic values of spare parts for petrol and electric vehicles, highlighting some significant differences. The type of vehicle, whether gasoline or electric, the number and percentage of resalable components, as well as the used value and profit, are identified.

Table 2. Economic comparison between Fiat 500 ICE and EV spare parts.

Vehicle Type	No. of Spare Parts	% of Saleable Spare Parts	Saleable Spare Parts	Value of Used Spare Parts (35%)	Used Realization (10%)
Petrol	465	15%	70	6.639 EUR	664 EUR
Electric	415	15%	62	4.679 EUR	468 EUR

First, petrol vehicles appear to have a higher total number of spare parts (465) than electric vehicles (415). This may reflect the greater mechanical complexity of internal combustion engines compared to electric ones, which tend to be simpler in structure.

Despite the different total number of parts, the percentage of saleable parts is the same for both vehicle categories, equal to 15%. However, this proportion leads to different results in terms of saleable parts: petrol vehicles have 70 saleable parts, while electric vehicles have 62. Turning to the economic aspects, the estimated value of used parts, calculated as 35% of the original value, highlights a gap: for petrol vehicles, the value is EUR 6639, while for electric vehicles it is EUR 4679. This gap can be attributed to the intrinsic value of parts, which could be higher in petrol vehicles due to the variety of components. Finally, the estimated actual revenues, obtained by considering 10% of the value of used parts, amount to EUR 664 for petrol vehicles and EUR 468 for electric vehicles. Again, petrol vehicles are more advantageous, although the difference between the two types of vehicles is not extremely marked.

In summary, the table highlights that petrol vehicles hold an economic advantage in terms of spare parts and residual value. Electric vehicles, while featuring a simpler design and fewer components, achieve comparable proportions of saleability and revenue. However, the data also suggest a notable variation in realization, with electric vehicles generating EUR 204 less in revenue (a decrease of 29.52%) compared to their petrol counterparts. Despite the ongoing shift toward electric mobility, petrol vehicles continue to offer a competitive edge in the used spare parts market.

An important note to consider is that the reduction in value of an EV at the end of its life is mainly due to the absence of an internal combustion engine and associated components, such as a catalyst. Furthermore, since the battery market is not yet regulated, their value is excluded from the analysis. Some assumptions were made for the calculation: on average, the value of used components of a vehicle is equal to 35% of the value of the

same new components. Furthermore, it is estimated that only 10% of the components of a car can be reintroduced into the market, instead of the theoretical 15%.

4.2. Scrap Sales

The following analysis considers the value of the recoverable scrap metal from the two scrapped Fiat 500s (ICE and EV), excluding the traction battery for electric vehicles as it must be treated separately. For this analysis, we have chosen the Fiat 500 for the same reasons previously mentioned. Additionally, selecting the same model enables a more realistic and comparable evaluation. The data in Table 3 show that electric vehicles, with a higher overall weight than petrol vehicles, generate a slightly higher scrap value (EUR 213 versus EUR 196).

Table 3. Economic comparison between scrap Fiat 500 ICE and EV.

Vehicle Type	Weight [kg]	Scrap Value [EUR/ton]	Value [EUR]
Petrol	980	200	196
Electric	1365 – 300 (battery) = 1065	200	213

This is mainly due to the higher net weight, even after considering a 300 kg reduction, associated with the battery and other specific components. We have assumed that the material composition is essentially the same for both types of vehicles, and, therefore, their value, which in the Italian market is typically around 200 EUR/ton, is also comparable.

However, electric vehicles, due to their greater weight, are more advantageous in terms of overall value, although the difference from conventional vehicles is not particularly significant. This comparison underscores how the greater weight of electric vehicles is mainly attributable to the presence of batteries and electric components, contributing, even if very marginally, to an increased salvage value in the scrap market. This advantage translates into a variation in revenue equal to +EUR 17, corresponding to an increase of 8.7% compared to internal combustion vehicles. However, this difference, although positive, is not sufficient to significantly change the overall economic panorama between the two types of vehicles.

It is important to note that the mass of the electric vehicle has been reduced by approximately 300 kg, which corresponds to the traction battery. This component requires specific disposal procedures and is, therefore, excluded from the scrap value. For the purposes of this calculation, the values in the table refer to the vehicle in its entirety, meaning they do not consider the potential removal and resale of components on the used market.

4.3. Comparison Between Native Electric Vehicle and Thermal Vehicle

To complete the analysis, two comparisons were carried out on two vehicles belonging to the same market segment, focusing on the difference in weight and value of the scrap. The comparison in Table 4 highlights a significant difference in scrap value between two cars from “compact vehicles” of the mid-range segment, oriented toward performance and comfort, with advanced design and technology.

Table 4. Comparison of scrap revenues of Tesla Model 3 (Native EV) and BMW 128 ti (ICE).

Vehicle Type	Weight [kg]	Scrap Value [EUR/ton]	Value [EUR]
Tesla Model 3 (EV)	1765 – 479 (battery)	200	257.2
BMW 128 ti (ICE)	1520	200	304

Although the Tesla Model 3 has a higher total weight (1765 kg compared to 1520 kg for the BMW 128 ti), a significant portion of its weight, equal to 479 kg, is attributed to the battery, which does not appear to contribute to the scrap value. This leads to a lower net weight (1286 kg) and, consequently, a lower overall scrap value (EUR 257.2).

In contrast, the BMW 128 ti, despite having a lower total weight, benefits from a fully valorized weight for the scrap calculation, resulting in an overall value of EUR 304. This represents a variation on realization of –EUR 46.8 (–15%) for the Tesla Model 3, highlighting how the exclusion of battery weight significantly impacts the scrap revenue of electric vehicles compared to internal combustion engine vehicles.

The comparison in Table 5 highlights a significant difference in scrap revenues between the two cars from the compact vehicles in segment B, focused on efficiency, versatility, and distinctive design, representing electric mobility and internal combustion engine mobility.

Table 5. Comparison of scrap revenues of BMW i3 (Native EV) and Fiat 500X 4x4 Cross (ICE).

Vehicle Type	Weight [kg]	Scrap Value [EUR/ton]	Value [EUR]
BMW i3	1270 – (250) (battery)	200	204
500X 4x4 cross	1430	200	286

The BMW i3, despite its lower overall weight compared to the Fiat 500X 4x4 Cross, suffers a further reduction in recoverable weight due to exclusion of 250 kg of the battery. This leads to a total scrap value of EUR 204, which is significantly lower than the EUR 286 of the Fiat 500X. In contrast, the Fiat 500X benefits from a fully recoverable total weight, allowing it to achieve a higher scrap value, despite a difference of only 160 kg compared to the total weight of the BMW i3. This results in a variation on realization of –EUR 82 (–29%) for the BMW i3, highlighting the economic disadvantage for electric vehicles in the scrap market due to the non-valorization of battery weight. It is important to note that the weight difference between electric and combustion engine vehicles is more pronounced in the case of the BMW i3 compared to the Fiat 500X. However, this difference must also be considered in the context of the smaller dimensions of the BMW i3 in comparison to the petrol vehicle.

5. Discussion

These comparisons, supported by multiple case study methodology, provided a clearer understanding of the economic and environmental differences between electric vehicles (EVs) and internal combustion engine (ICE) vehicles. By analyzing similar models with different powertrains, it was possible to isolate the scrappage values and profits derived from their sale. Furthermore, this approach enabled a realistic, data-driven comparison, making the results particularly applicable to the Italian context, with a focus on popular models such as the Fiat 500.

The aim of this study was to evaluate the economic and environmental benefits of a fully established recycling process, particularly for end-of-life vehicle dismantling. However, barriers to entry for new participants in the sector were not considered. As a result, the observed economic and environmental benefits may appear higher than those expected in more complex and realistic scenarios.

The omission of fixed costs associated with adopting new recycling technologies and devices, as well as the lifecycle greenhouse gas emissions of EV batteries, is due to a lack of clarity in battery management and a scarcity of regulatory references. The high investment costs for recycling technologies, combined with the absence of clear national directives and adequate incentives, represent a significant economic barrier to entry for new entities in the sector. Nevertheless, these fixed costs are expected to decrease progressively as

recycling processes improve and larger volumes of vehicles and batteries are processed. This scalability will allow investment costs to be spread over a larger number of units, enhancing the long-term economic viability of recycling.

Additionally, the limited availability of scrapped EVs, coupled with the high costs and technical complexities of battery recycling, make it difficult to draw definitive conclusions from assessments based on a small number of vehicles. A more comprehensive evaluation will require data from large-scale operations to ensure robust conclusions and representative results.

The simulations presented in this study are based on assumptions made by the research team, which were necessary due to the following reasons:

- The near-total absence of scrapped EVs;
- The limited availability of data on the market for used EV components.

These limitations may affect the accuracy of the estimates and conclusions as they do not fully reflect market dynamics and emerging technologies in the sector. Future studies will be needed to address these gaps by integrating data from newly developed recycling facilities, considering the fixed costs of technology adoption, and analyzing the environmental implications of scaling up recycling processes.

6. Conclusions

This study explored the topic of the scrapping and recycling of end-of-life vehicles, with a focus on the distinction between internal combustion engine (ICE) vehicles and electric vehicles (EVs). The analysis highlighted the main critical issues and potential of a constantly evolving sector.

The main challenges of the automotive sector were illustrated with particular attention to the transition to electric mobility and the implications of environmental regulations, such as the European Directive 2000/53/EC. This regulatory framework emphasizes the importance of recovering 95% of the average weight of an end-of-life vehicle, with 85% of this recovery destined for reuse and recycling.

An economic model was exploited and used as a basis for simulating the value deriving from the scrapping of ICE and EV vehicles. This model was integrated with data from interviews carried out with a small portion of Italian dismantlers, paying particular attention to internal combustion vehicles. Simulations were then produced to quantify the revenues deriving from the sale of used components and scrap metal.

The analyses were carried out through the analysis of case studies in three main contexts: the sale of spare parts, the sale of scrap, and a comparison between vehicles of the same segment. For electric vehicles, the value of saleable spare parts was 29.52% lower than for petrol vehicles, mainly due to the absence of an internal combustion engine and other key components. The value of scrap of an electric vehicle instead can be up to 29% lower; in fact, despite the greater overall weight of electric vehicles, the need to treat the traction battery separately reduces its weight and also reduces the value of scrap. In conclusion, the transition to electric mobility brings new economic and operational challenges for the demolition and recycling sector. Battery management represents one of the most critical aspects for an EV; in fact, their movement is not yet fully regulated, and their disposal requires specific procedures that increase overall costs. To improve recycling efficiency and maximize the economic value derived from the scrapping of electric vehicles, it is necessary to develop advanced technologies for the recycling of traction batteries, create a regulated supply chain for the marketing of used electrical components, and implement specific economic models for electric vehicles. The evolution toward more sustainable mobility requires a joint commitment of institutions, operators in the sector, and the automotive

industry to address challenges related to the management of end-of-life electric vehicles, ensuring the environmental and economic sustainability of the entire process.

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