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Circular Economy in the Automotive Industry: A Study on End-of-Life Vehicles Management and Circular Economy Strategies

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Abstract

The circular economy framework takes a different approach on how products are designed, used and disposed of by creating a closed-loop system that optimizes the use of resources. This thesis focuses on End-of-Life Vehicles (ELVs) and their role in the circular economy framework, as the automotive industry faces increasing pressure to reduce its environmental footprint and increase resource efficiency.

Due to the presence of valuable metals, polymers, and other materials, all of which are increasingly seen as key resources in the context of urban mining, vehicles that reach End-of-Life (EoL) present considerable potential for material and part recovery.

The role of ELVs in the context of circular economy is analyzed by exploring the transition from the ELV Directive (2000/53/EC) to the new proposed ELV Regulation. The research investigates how regulatory shifts impact the management of ELVs, focusing on the integration of these vehicles into circular economy strategies. Additionally, it highlights significant regulatory developments and their expected impacts on the automobile industry.

Some of the issues that are analyzed include the challenges related to dismantlability, material recovery, and the efficiency of recycling processes within the context of ELV processing. Among the issues highlighted in this paper, one key issue is the difficulty in achieving higher recycling purity and reuse rates for materials and parts coming from ELVs.

Technological limitations, particularly in terms of dismantling and material separation, limit the efficiency of recycling operations. Additionally, a lack of collaboration between stakeholders, such as Original Equipment Manufacturers (OEMs), Authorized Treatment Facilities (ATFs), shredders, and recyclers, further limits progress toward more effective ELV management. Enhancing communication and cooperation among these actors is essential to improve the recovery process and optimize the reuse of materials.

The thesis also highlights the importance of reducing impurities in recycled materials, which currently hinder the presence of recycled content in new vehicles. Therefore, investments in advanced technologies are needed to improve the quality of recycled materials.

In conclusion, this thesis underscores the potential of ELVs as a valuable resource within a circular economy framework. By focusing on regulatory evolution, industry collaboration, and technological innovation, the research contributes to understanding how the automotive sector can successfully transition towards more sustainable practices.

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1. Introduction

The circular economy framework provides the foundation for a sustainable management of the resource we use in our daily lives. Its main 3 pillars, as detailed by the Ellen MacArthur Foundation are:

- Eliminate waste and pollution
- Circulate products and materials (at their highest value)
- Regenerate nature

In the automotive sector, the principles of the circular economy, especially in the form of reuse, refurbish and remanufacturing are currently being slowly developed and applied, and it is therefore crucial that such sector insert circular economy as a central topic of the business.

This transformation needs to be applied to all stages of its supply chain, and while major changes are happening at the use phase stage to decrease the emissions related to the circulation of vehicles, the same attention is not yet present in stages beyond the use phase such as in the recirculation of recycle material back into the production of vehicles or the reuse and remanufacturing of parts and material coming from end-of-life vehicles (ELVs).

With millions of vehicles reaching End-of-Life (EoL) each year, the effective dismantling, recycling and reuse of vehicle's components is fundamental for the industry to finally close the loop. ELVs represent a viable source of secondary raw material and need to be therefor included into urban mining strategy to ensure that the sector can become less and less reliant on raw materials.

The European Commission has recognized the importance of such vehicles and addressed the related problems with the so called ELV Directive (Directive 2000/53/EC), with articles addressing not only the dismantling of critical parts and hazardous substances, but also on the introduction of the design for dismantlability for OEMs and targets for reuse, recycling and recovery across the supply chain.

Due to the complexity of such products and to enhance further the application of the circular economy framework across the supply chain, a new Regulation was proposed in 2023. With more articles and the introduction of new targets such as the presence of recycle content of 25% in new vehicles, 25% of which must come from ELVs, the Regulation is trying to move even more the sector towards circularity.

This thesis explores the importance of the automotive sector in present days through an overview of recent trends in technology, materials, emissions and waste generated. It will then dive into the regulatory framework related to ELVs, by showing the main articles and differences between the ELV Directive and the new proposed ELV Regulation.

The ELV supply chain will be also explained by detailing the various actors and their current roles, as well as the process that is used to handle vehicles among the different actors. An overview of the current dismantling practices in 3 major Member States of EU it's also present to understand how the Directive translated in their legislative framework.

To understand how the automotive sector can improve current circular economy practices, the case of Renault "The Future is Neutral" is showcased in particular as a good example of commitment done by an OEM to achieve a higher level of circularity. As vehicle are highly dependent on the design and material choices from OEMs, it's crucial that automakers start collaborating more with the different actors.

Finally, current challenges in the ELV management will be explained to understand what are the main problems of such system and what improvements could be made. While the literature mainly focuses on recycling issues either from the overall vehicle point of view or related to single components, impact assessments made by the European Commission and related bodies shows that also other areas need to be improved to also increase the current demand for reused parts.

By shifting the market towards recycle materials, remanufacturing and reuse, the overall supply chain can benefit by aiming towards higher efficiency and recovery purity in its various stages.

The thesis aims to answer the following research questions:

- What are the main challenges in ELVs management?
- What opportunities exist for an improved collaboration between OEMs, ATFs, and policymakers to enhance the circularity of the sector?

2. The Automotive Sector: Trends and Challenges

The automotive sector has been subject to important transformation, especially due shifting consumer preferences as well as new regulatory changes. A growing emphasis on sustainability, with the rise of electric vehicles (EVs), as well as the growing technology presence, are changing the current composition of our vehicles as well as their impact on the environment.
This chapter will explore the current situation of the industry, the reported trends and regulations affecting the European market as well as the current composition of vehicles.

2.1. Overview of the Sector

2.1.1 Market Size Worldwide

The automotive market is one of the largest worldwide, and while it's still recovering from the decrease in sales and supply chain disruption from the pandemic, it was evaluate at 3.4 trillion € in 2023 (Spherical Insight, 2024). A study published by Towards Automotive projects that by 2031, the global automotive industry is expected to grow to a valuation of 6.15 trillion €.

In 2023, global car sales experienced a strong recovery, reaching an increase in 10% and by exceeding 72 million units, as supply chain disruptions began to ease. Europe saw an impressive 18.6% increase in car sales over 2022, driven by the recovery in both Western and Eastern European markets. Meanwhile, China's car sales exceeded 22 million units in 2023, reflecting a 4.5% growth from the previous year. The Chinese market now represents about 31% of global car sales, highlighting its pivotal role in the global automotive landscape.

In the past few years, the automotive industry has been growing steadily, but at different rates in different regions. Countries like China and India have been driving most of the global sales, while more developed markets like Europe and North America are growing more slowly due to the maturity of the market and because of stricter environmental laws and regulations.

When looking at automakers, Toyota Group remained the world's biggest carmaker in 2023, with over 11.23 million vehicles units sold, accounting for about 11.18% of global car sales. It represented a 7.2% increase compared to the 10.48 million units it sold in 2022. Volkswagen Group, the next best, delivered around 9.24 million motor vehicles in 2023, an increase of 11.8 % from just over 8.26 million in 2022 (Statista, 2024).

BYD and Tesla reported a strong growth in the electric vehicle market:

- BYD sold over 3 million units in 2023 against 1.82 million units in 2022, which is an increase of 67% (BYD, 2024). The company stands over its competitors in the EV sector.
- Tesla also reported more than 1.77 million units in 2023, a 31.91% increase compared to 1.34 million units sold in 2022 (Tesla, 2024).

These trends show the continued recovery of the global automotive market, the evident shift to electric vehicles, and continued growth of the emerging markets.

2.1.2 European Union Market

As reported by ACEA, in 2024 Battery-electric vehicles (BEVs) have grown in popularity among European customers, becoming the third most preferred option. In December, their market share reached 15.9%, bringing their annual share to 13.9%. This exceeded diesel vehicles, which held steady at 11.9%.

In 2023, BEV sales exceeded 1.5 million units, marking a 37% increase from the previous year. Petrol-powered vehicles still held the largest share at 35.3%, with hybrid-electric vehicles (HEVs) in second place at 25.8%.

When it comes to production, the European Union manufactured a total of 12,126,604 vehicles in 2023, up by 11.3% from 2022’s 10,896,821 units. Despite this growth, production numbers have not yet returned to pre-pandemic levels, which were at 14,096,444 units in 2019.

The EU car market showed solid growth in 2023, increasing by 13.9% over the previous year, reaching a total of 10.5 million units. Key markets such as Italy (+18.9%), Spain (+16.7%), France (+16.1%), and Germany (+7.3%) contributed heavily to this increase. However, when compared to pre-pandemic years, the number of vehicle registrations remains 19% lower than the 13 million units seen in 2019.

In respect to other countries, Europe is slowly reaching the number of sales before the pandemic and seems to struggle in offering competitive options to its consumer especially in comparison with the rising Chinese vehicles.

2.1.3 Growth (and Trends)

Today's economies are dramatically changing, moved by development in emerging markets, the accelerated rise of new technologies, sustainability policies, and changing consumer preferences in regard to ownership. Based on the , four major trends are affecting the automotive sector:

1. **Autonomous driving**: passenger vehicles in Europe and North America will reportedly have an increased amount of level-three and level-four automation features, which will make them highly automated or capable of self-driving on highways by 2025. The "Autonomous driving's future: Convenient and connected" 2023 report by McKinsey shows that this market could create massive value for the auto industry, due also to the high component costs, and reduce the number of car accidents and collisions by therefor limiting the number of consumers requiring assistance and repairs. At the same time these vehicles, by requiring a more advanced technology and therefor an higher number of sensors and cameras in the vehicle, could become more difficult to dismantle. The increased complexity and number of components may lead to difficulties in locating and disassembling them efficiently for recycling, which could in turn increase the problems in achieving high recovery rates and complying with current End-of-Life Vehicle (ELV) directive.
2. **Electrification**: a significant and rapidly growing segment within the global market is electric vehicles (EVs), as shown in the previous chapter. This growth is driven by the increasing availability of charging infrastructure, government incentives for sustainable mobility solutions, and increasing consumer demand for environmentally friendly vehicles. In some regions, EVs are expected to make up a significant portion of total vehicle sales by 2030, as governments are expected to meet the ambitious targets for emission reductions and therefor promote electrification. A clear example is the case of the Tesla Model Y, which became the most popular car model worldwide in 2023, selling 1.23 million units, an increase of 64% from the previous year. The growing market of EVs is also affecting the demand for critical materials

such as lithium, cobalt, nickel and manganese as well as rising new challenges in the removal and recycling of the batteries.

3. **Connectivity**: McKinsey estimates that more than 90% of vehicles sold in 2030 will be connected, allowing drivers to access a large amount of useful information regarding their vehicle. Additionally, connected cars will gather data during their own operation and therefor help automakers and customers extend the life of their vehicle, increase its operational efficiency, and save money on repairs. The more information are available on the status of the vehicle, the easier it is to understand the current state of its parts and components, and therefor also increase any future possibility of parts re-use with targeted maintenance that can increase the life of the vehicle and offer a clearer economic value at the EoL of the vehicle.
4. **Shared mobility**: shared mobility, which includes ride-hailing services, is becoming a more frequent selected option for consumers that look for transportation options that are convenient, affordable, and eco-friendly. This segment could generate up to $ 1 trillion in revenues by 2030. These new forms of urban mobility can lead to fewer vehicles on the road, as users tend to delay or avoid purchasing personal cars (George and Julsrud, 2019), therefor reducing in the long term the vehicles that reach the end-of-life and positively impacting the waste stream.

These trends are impacting the automotive sector by opening to new opportunities and challenges. As the industry needs adapts to these changes in all stages of the supply chain, it will not only affect the way vehicles are designed, produced and consumed, but also impact their treatment at EoL, a fundamental part of the circular economy strategy.

2.2. Environmental Impacts

2.2.1 Contribution to Global Emissions

As reported in 2021 by Our World in Data, transportation is the second-largest contributor to global greenhouse gas (GHG) emissions, reaching 7.84 billion metric tons of CO_2 equivalent annually, followed by the electricity and heat production sector.

The same outcome is reported when considering just CO_2 emissions by sector, with transportation taking again the second spot, with 7.63 billion metric tons of CO_2 annually. When looking at the European emissions, the value is reportedly 765.01 million metric tons of CO_2 annually, showing the importance of introducing policies to reduce the impact of the industry.

The majority of the emissions related to transportation comes from road vehicles, which account for 15% of global GHG emissions in 2023 according to Statista. Among road vehicles, light-duty vehicle, primary passenger cars, contribute to the largest portion of these emission. Additionally, since 2010 the emission from passenger cars have been increasing at around 1% per year, reaching over 3.5 billion metric tons of CO_2 in 2021.

The results of such amounts of emissions is mainly due to the sales growth of the market during the years, that still relies heavily on internal combustion engines (ICEs). However, the rise of EVs in the market is currently offering a reduction in the emissions for the future by decreasing the emissions related to the use phase but shifting part of the emissions upstream, at the production stage and material extraction. As highlighted by Koroma et. Al (2022), Battery Electric Vehicles (BEVs) emissions at use phase significantly decrease and the production and manufacturing of batteries contribute considerably to the overall carbon footprint.

Given the current (and future) state of the sector and its impact on the environment, the European Commission has developed and established policies with the purpose to accelerate the reduction in emissions through more sustainable technologies that can ease the achievement of the carbon neutrality target. Additionally, the focus cannot stop at the use phase of such products but it needs to target the emissions that also comes from the rest of the supply chain with policies that enables an increased attention to cardinal points of the circular economy framework such as the elimination of waste through the continuous circulation of parts and materials.

2.2.2 Policies Addressing Emissions Reduction

Several policies and regulations have been implemented by the European Union to reduce the emissions from the transport sector, particularly those from passenger cars and light commercial vehicles, which together accounts for around 19% of the total CO_2 emissions in the EU.

These measures are part of the EU's effort to achieve climate neutrality by 2050:

- **EU Green Deal:** launched in 2019, the European Green Deal is the EU's strategy for achieving climate neutrality. As suggested by the name, this initiative represents the European Union's effort to establish a green transition, including a diverse range of policies aimed at decreasing emissions in multiple sectors, such as transportation.
- **Sustainable and Smart Mobility Strategy**: As part of the EU Green Deal, the European Commission defined this strategy in 2020 with the purpose to make the transport sector more sustainable. It focuses on a important shift, with a goal of reducing emissions by 90% by 2050. The strategy includes milestones for 2030, 2035, and 2050, such as having 30 million zero-emission vehicles (ZEVs) on European roads by 2030, and nearly all cars, vans, and buses being zero-emission by 2050. In addition, it emphasizes the importance of a multimodal transport system, including rail, aviation, and maritime transport, as well as a strong policy framework to reduce fossil fuel dependence and promote sustainable alternatives.
- **Fit for 55 package:** this set of legislative proposals aims to align the EU's policies with the 2030 climate targets of reducing net greenhouse gas emissions by at least 55%. As part of this package, Regulation (EU) 2023/851 is particularly relevant for the automotive sector. It strengthens previous emission reduction targets for vehicles, setting a 55% reduction for passenger cars and 50% for light commercial vehicles by 2030, compared to 2021 levels. Additionally, this regulation introduces more stringent requirements for the adoption of zero- and low-emission vehicles (ZLEVs), with at least 25% of new passenger cars and 17% of new light commercial vehicles to be ZLEVs by 2029. By 2035, the regulation sets a fleet-wide target of 100% reduction in CO_2 emissions for both new passenger cars and light commercial vehicles which is currently imposing important shifts for the automakers and the customers.
- **Incentive mechanism for zero - and low-emission vehicles (ZLEVs)**: From 2025 to 2029, a ZLEV crediting system will apply for both car and van manufacturers. The system will alleviate a manufacturer's specific emission target if the share of new ZLEV (vehicles with emissions between 0 and 50 g CO_2/km) registered in a given year exceeds the following benchmarks: cars – 25% ZLEV, vans – 17% ZLEV. A one

percentage point exceedance of the ZLEV benchmark will increase the manufacturer's CO_2 target (in g CO_2/km) by one percent. The alleviation of the emission target will be capped at a maximum of 5% to safeguard the environmental integrity of the Regulation.

- Euro 7: due to the fact that new combustion cars and vans will be banned on the internal market from 2035, the European Commission has set other measures to make sure that existing combustion cars made before 2035 still control their CO_2 emissions. The Euro 7 emission standards, which will come into effect from 2026, are designed to reduce the emissions of both light- and heavy-duty vehicles. These stricter standards will apply to all new passenger and commercial vehicles, including new limits on particulate emissions from brake pads and tires, as well as more stringent nitrogen oxide and particulate matter limits for heavy-duty vehicles. Additionally, the regulation includes measures to ensure that vehicles manufactured before 2035, especially those with combustion engines, comply with new CO_2 emission standards. Euro 7 also introduces durability requirements for electric vehicle batteries, requiring them to retain at least 80% of their energy capacity after five years or 100,000 kilometers.

These policies and regulations highlight the EU's strong commitment to reducing emissions in the transport sector, particularly through the promotion of zero- and low-emission vehicles such as BEVs. The regulatory framework, driven by the EU Green Deal and the Fit for 55 package, has significantly influenced manufacturers' increasing focus on EVs.

These regulations not only incentivize manufacturers to accelerate the development of BEVs but also create a future where traditional internal combustion engine vehicles (ICEVs) may no longer be viable. As a result, the push for BEVs is driven not just by market demand but, more importantly, by regulatory requirements aimed at meeting the EU's ambitious climate targets.

Manufacturers must innovate rapidly to meet these goals, or face penalties for non-compliance, as the regulatory landscape continues to evolve. Exceeding the CO_2 emissions target trigger penalties for the manufacturer. For each new vehicle registered that year, the manufacturer must pay an excess emissions premium of €95 per gram of CO_2 per kilometer over the target.

2.2.3 Recent Trends in Emission Reduction

Due to the above-mentioned policies and regulation, the automotive industry is currently transforming to be able to maintain stability in the market by achieving the requested targets. These mentioned regulations, focus primarily on reducing Scope 3 emissions, which are a significant portion of the overall emissions from Original Equipment Manufacturers (OEMs).

As a result, the industry is shifting toward more sustainable technologies, with a notable rise in hybrid and electric vehicles (EVs). These vehicles help reduce CO_2 emissions while combining also innovation in lightweight materials and energy-efficient designs.

Additionally, regulations are pushing for increased recyclability and support for the circular economy. Manufacturers are now encouraged to use materials that are easier to recycle and to minimize the environmental impact of vehicles during their EoL stage. These regulatory changes are reshaping the automotive industry's approach to sustainability, influencing everything from design to material selection and powertrain technologies.

Key technologies that have emerged as part of this shift include:

- **Hybrid Electric Vehicles (HEVs)**: since electrification is the main protagonist of the shift towards zero carbon emissions, OEMs started introducing vehicles powered by an ICE coupled with a battery. Depending on the capacity and fully electric range of the vehicle, different denominations risen:
    - **Mild Hybrid Electric Vehicle (MHEV):** among the hybrid vehicles this system is the one equipped with the smallest battery, usually in the form of 48 volt electric systems. A mild hybrid usually just assists the ICE during acceleration from a dead stop and assist in giving energy on systems like the air conditioning. The battery is usually recharged either through regenerative breaking or also from the gasoline engine.
    - **(Full) Hybrid Electric Vehicle ((F)HEV)**: full hybrid vehicles also come equipped with both a gasoline engine and an electrical component. However, the electrical component in a full hybrid vehicle is capable of handling far more of the workload than that of a mild hybrid. Most full hybrids can actually operate for some distance solely on electric power. They're equipped with 2 main types of powertrains:
        - Parallel hybrids, the engine can be powered in one of 3 ways: directly by the engine, directly by the electrical motor, or by both systems working together.
        - Series hybrid, the wheels are powered solely via the electric motor, with the gasoline-engine providing power for the electric motor, sort of like a generator. The gasoline-engine never actually powers the wheels.
    - **Plug-in Hybrid Electric Vehicle (PHEV)**: the main difference with plug-in hybrids is that these vehicles can charge their batteries via external chargers as well as internal. As a result, plug-in hybrids usually have greater electric-only ranges than full hybrids. Plug-In hybrids essentially serve as a half-way point between full hybrid vehicles and fully electric vehicles.
- **Battery Electric Vehicles (BEVs)**: unlike HEVs, the vehicle is propelled only by the electric motor so that no combustion engine, fuel tank, or even exhaust system is needed. The vehicle is charged either by recuperation or by the power grid. As there is a wide range of vehicle concepts for pure electric vehicles, the technical features regarding the electric motor or the capacity of the battery can differ considerably. Compact cars currently have a capacity of around 15–25 kWh, whereas vehicles in premium segments can be equipped with a battery system with a capacity of 60 kWh or more.
- **Fuel Cell Electric Vehicles (FCEVs)**: FCEVs use a propulsion system similar to that of electric vehicles, where energy stored as hydrogen is converted to electricity by the fuel cell which is then used to power an electric motor. A battery pack is used to store energy generated from regenerative braking and provides supplemental power to the electric traction motor as well as to smooth out the power delivered from the fuel cell with the option to idle or turn off the fuel cell during low power needs.
- **Lightweight materials**: exploring lightweight materials for automobiles is among one of the strategies followed by OEMs mainly to save weight and enhance the overall

vehicle performance. A study on Advanced lightweight materials (Zhang and Xu, 2022), categorized them into 4 major categories:

- Light alloys (e.g., aluminum, magnesium, and titanium alloys): light alloys are apparently promising substituents for steel and cast iron to reduce the vehicle weight while improving the component performance, particularly in high-end models.
- High strength steel (HSS) family (e.g., conventional HSSs and AHSSs): the substitution of mild steel with HSSs seems to be a more practical choice to produce affordable components and achieve a weight reduction. However, one major challenge for HSSs is how to achieve a balance between strength and ductility.
- Composites (e.g., carbon fiber reinforced plastics or CFRP): they are perfect candidates for both exterior and interior components of automobiles, although the development of appropriate manufacturing techniques is still lacking for mass production with lower costs.
- Advanced materials (e.g., mechanical metamaterials): The latest research focuses on advanced materials like metamaterials, which offer unique properties such as enhanced impact resistance, stiffness, and energy absorption. These materials may revolutionize automotive design, enabling lighter, safer, and more efficient vehicles.

The rise EVs, the increase technology present in vehicles and the adoption of advanced materials has increased the use of copper, critical raw material (CRM) and high strength steel in vehicles, therefore increasing the emissions at the extraction stage for such materials, highlighting even more the importance of introducing an higher percentage of recycle content in vehicles, and additionally making the automotive industry’s supply chain less exposed to external events that can cause general disruptions of the supply chain and, therefore, a possible increase in price of electronic components and delays in the supply.

2.2.4 Evolution of End-of-Life Vehicles Waste in Europe

While the industry has been focusing on reducing emissions, another critical environmental challenge remains the management of end-of-life vehicles (ELVs). As the sales of vehicles steadily increased over year the volume of ELVs has also grown.

Analyzing the amount of waste generated from such products it’s crucial to understand why policies at European level can mitigate its impact on the environment.

By looking at the data showed in for passenger cars reported by Eurostat for 27 countries of the European Union regarding the vehicle fleet, new vehicle and ELVs it can be seen that the ELVs are on average 5,3 million per year over the last reported 10 years. This has translated in 5,85 million tonnes of waste yearly over the considered period.

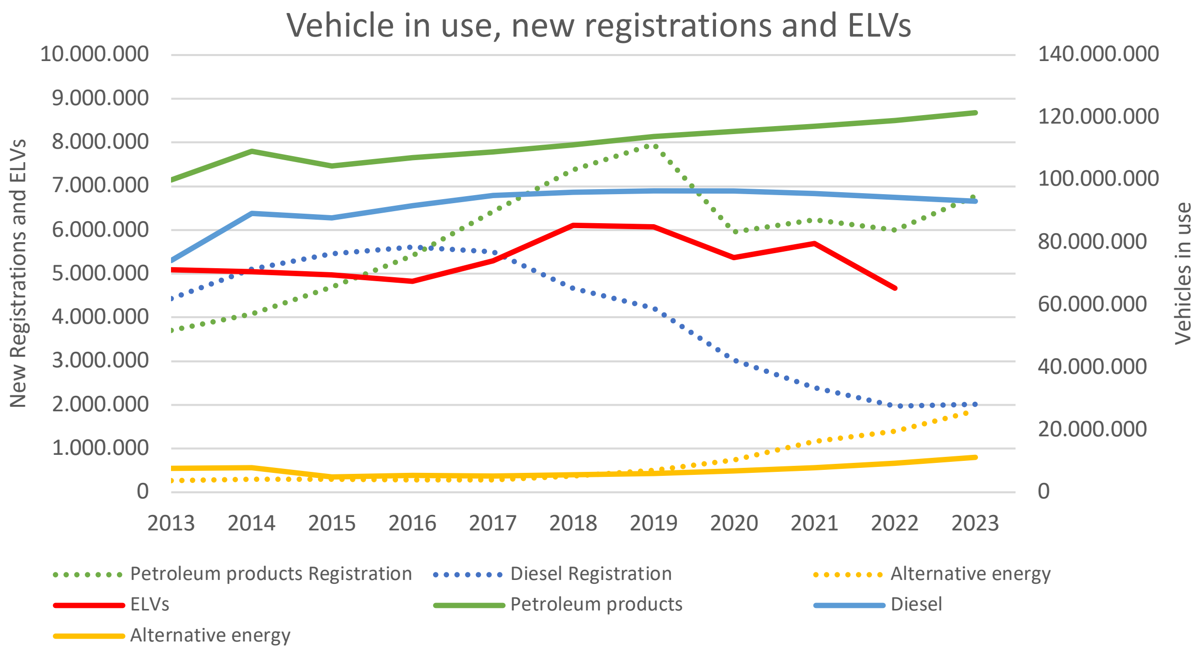

Figure 1. Comparison between vehicle is use, new registrations and ELVs (Source: personal elaboration of data regarding "New passenger cars by type of motor energy [road_eqr_carpda]", "Passenger cars, by type of motor energy [road_eqs_carpda]" and End-of-life vehicles – Waste generate [env_waselvt] by Eurostat)

While the exact number of missing ELVs cannot be determined, the European Commission estimates that around 3.5 million vehicles disappear without a trace from EU roads each year. More pessimistic estimates are instead reported by EGARA (European Group of Recycling Associations) which account between 4 and 8 million vehicles to disappear every year. This entails that some materials are not re-entering the supply chain properly and may cause harm to the environment.

The decline of diesel vehicle in registrations translates also in their decline in the vehicle fleet composition by getting slowly replaced by alternative energy vehicle, the largest share of which is composed of vehicles powered by electricity, immediately followed by LPG vehicles: BEVs accounted for just 50k unit in 2013 while in 2023 they reached 4,4 million units in the European fleet.

Vehicle powered entirely or partially (hybrid and plug-in hybrid petrol-electric) by petrol still remained the largest share of the fleet which has been constantly growing from 2015: fully petrol vehicle grew from 67,8 million in 2013 to 110,8 million in 2023 while hybrids grew from just 0,2 million in 2013 to 10,8 million in 2023.

If we consider the average age of passenger vehicle to be around 12,3 old in Europe, with average lifespan that can vary from 8 to 35 years, it's important to take into consideration the lag time that applies to ELVs: the rate at which vehicle ages and reach EoL impact the waste stream and the recycling routes.

While more BEVs will start to reach EoL, it's important to take into consideration this lag time also when establishing policies to manage these waste streams.

The positive effects that are expected to rise from the implementation of circular economy principle to the automotive industry on the vehicles of today may see the real effects on the environment only more than a decade later.

2.3. Material Usage

2.3.1 Metals

The automotive industry has evolved noticeably in the last decades due to the need of increased fuel efficiency of cars, lower down costs and emissions, and reduce the vehicle's weight without losing its strength. Therefor the material composition of vehicles is changing in recent years.

Metals are the most used type of material in vehicles. While precise estimates cannot be made regarding the exact composition of metals in cars, mainly due to the many different models and brands in circulation, both in the past and present the majority of the metals share is composed of steel. This has been consistently reported in the literature and a comprehensive review by Ortego et. Al (2019) shows the composition of vehicles both in terms of power-type (ICEV, PHEV and BEV) and in respect to components such as body, electrical and electronics, powertrain and batteries.

When looking at the overall material composition of such vehicles, as shown in Figure 2 below, Fe and Al together make most of the metals composition of vehicles (respectively 90,88%, 90,37%, 84,62%, 79,52%), independently of the type of power-train.

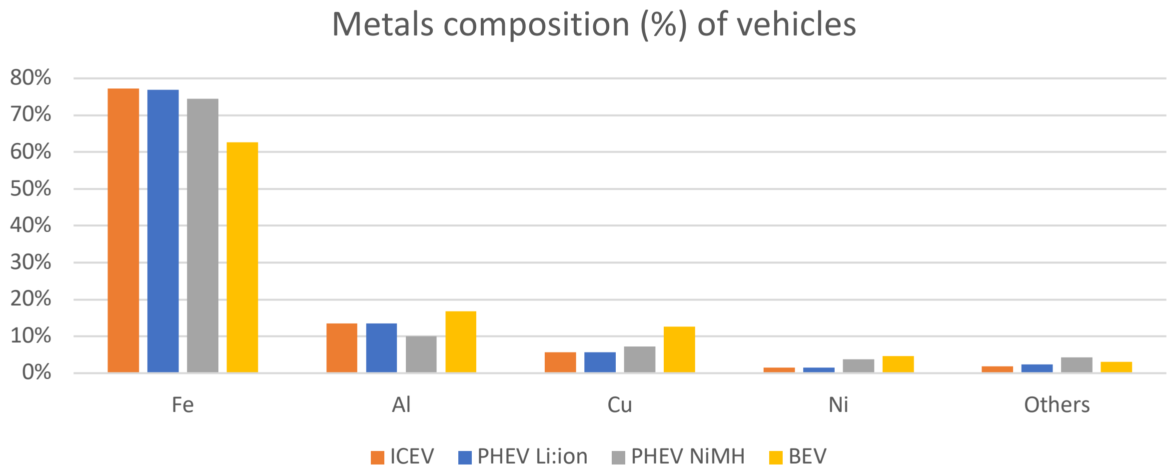

Figure 2. Metals composition (%) of vehicles
(Source: personal elaboration of data reported by Ortego et al., 2019)

The presence of an ICE substantially increases the impact of Fe while the value drop to 62,73% for BEVs due to the materials used for the batteries, that without the thermal engine, occupy much more space due to the need for an increased capacity in respect to PHEVs.

While weight is a good indicator of the composition of the vehicle, it is not enough to fully understand the impact of such materials. When we evaluate also the effect of using such materials on the supply chain and how they affect emissions, several other metrics needs to be accounted such as the difficulty of the extraction, the energy demand and the possibility to recycle such material at EoL and the purity of the obtained recycled materials.

Therefore, Ortego et. Al (2019) introduces the concept of thermodynamic rarity as another metric in order to account the exergy cost (GJ) needed for the production of such material and therefore allocate a greater weight to the materials that are more valuable. Due to the presence of a higher amount of critical material in electrified vehicles, rarity increases offering another perspective on the impact of the overall metals.

Even if the majority of the mass is due to iron, by considering its rarity the share rate drops to 15% while Al increases to 40% and therefore the positive impact that Al has for light-weighting purposes have instead a negative connotation where rarity is considered.

While the current ELV Directive is based solely on mass approach of the materials that are recycled from ELVs, another metric such as the thermodynamic rarity of the material offers an important contribution on a different approach in evaluating and setting the recycling targets for EoL.

As the automotive industry shifts towards ZEVs and the demand for rare materials will increase, the material rarity will decrease in comparison to ICEVs. Additionally, the use of such metric could offer OEMs an additional tool to understand what parts should be easier to remove from vehicles to ensure that they're fully recovered at EoL and re-immitted in the supply chain.

While body and powertrain masses have the highest contributions in all types of vehicles, the situation changes, across the various type of vehicles, when rarity is considered mainly due to the presence of batteries and electronic components.

2.3.2 Plastic

Plastic is the second most used material in vehicles after metals as it offers mass reduction and technical properties useful both for internal and external parts of the vehicle. As reported by Automotive Plastic (2019), polymer composites in light vehicles have increased from less than 9 kg per vehicle in 1960 to 160 kg per car in 2018.

Considering an average weight for modern car of 1,500 kg, between 12-15% is composed of plastic materials (Plastic Europe, 2021) depending on the type of vehicles and the equipment in use. This translated in the automotive sector being the third biggest application for plastic in Europe and generated 1.6 million tonnes of plastic waste in 2022 with 19% reported as recycled.

The immediate benefits of such material is related to weight and therefor on the decrease in the vehicle's fuel consumption and emissions: as reported by Plastic Europe, reducing the weight of the bodywork of an average car by 100 kg cuts the CO2 emissions by 10 gr/km.

Plastic can be found in several areas of the vehicle such as:

- external parts in bumpers, head and rear lights, wheel covers and various trims
- internal parts in door's trims, dashboard, seats and pillars cover
- under the hood in manifolds and fuel systems

with reported use of 53% in interior, 20% in exterior, 14% under the hood and 13% in electric/lights (Plastic Europe, 2021).

The various components highlight the broad range of application that the material offers. In particular, according to EURIC (2021), the polymers used in vehicles are largely composed of polypropylene (35%), polyurethane (19%), polyamides (11%), and polyvinyl chloride (9%), with polypropylene making up the largest portion. The decision on the type of polymers is based on the needs of the manufacturers and some advantages includes (Patil et. Al, 2017):

- Minimal corrosion, allowing for longer vehicle life
- Substantial design freedom, allowing advanced creativity and innovation
- Flexibility in integrating components
- Safety, comfort and economy

- Recyclability

With the continuous increase of plastic in vehicles, it's important to address the problematics that can arise at EoL to make sure that the rate of recycle plastic increases while also ensuring that recycled plastic, either coming from ELVs or other industries, is introduced in vehicles, which is rarely happening in present vehicles.

As reported by Maury et. Al (2023), the presence of recycle plastic in the automotive sector is far behind other industries such as Building and construction (46%) and Packaging (24%) and that the majority of the recyclates used in the vehicles come from pre-consumer sources mainly because of the presence of less contaminants than post-consumer materials which poses uncertainty in the composition of the material, its quality and therefore on its use.

2.3.3 Elastomers

Elastomers, commonly known as rubbers, account for around 5% of the vehicle's mass (Plastic Europe, 2021). Tires, seals, gaskets, hoses, tubes, soft, and damping parts are commonly made of rubber with tires having the highest share.

The EU is responsible of 12.5% of waste tire generation and recovered 91% of the generated End-of-Life Tyre (ELT) with a 53% of material recovery and 34% of energy recovery, mainly in cement kilns (Bockstal et. Al, 2019).

Such high % of energy recovery can be explained by the composition of tires. Passenger car's tires can be made of at least three or four types of rubbers: NR, SBR, BR and IIR (Utrera-Barrios et. Al, 2023). This highlight their complex chemical and mechanical structure which is created for durability and abrasion resistance which also impacts the quality that can be achieved through recycling which is currently not equivalent to vehicle grade.

Therefore, an improved recycling system is needed to make sure that tires are appropriately recycled from ELVs.

2.3.4 Glass

Glass accounts for around 3% of the overall mass of the vehicle (Plastic Europe, 2021), and can be found in the windshield, tailgate window, the doors window and mirrors. Glass can be either:

- Laminated: it's composed of two sheets of glass held together by a sheet of PVB in between. This composition, which is typical of the windshield, will ensure that in case of collision the glass will not shatter, eliminating the possibility of injuring the passengers.
- Tempered: this type of glass is created by heating and then rapid cooling, therefore making it 10 times stronger than normal glass. In case of a collision, tempered glass, unlike the laminated one, will indeed shatter but into small pieces, reducing the risks of injuries of the passengers.

The current supply chain of glass for the automotive industry, as reported by Glass for Europe, highlights the current issues that arises from such material especially coming from its treatment at EoL. Less than 10% of the times glass is currently dismantle from ELVs, due to low revenues that don't over the cost of dismantling, and, by being left on the vehicle, prevents the cullet from being recycled properly into new glass products.

While current practices lead to downcycling, especially for backfilling, manual and mechanical dismantling can indeed help reducing the raw material consumption due to a market where on average demand for glass cullet exceeds supply in Europe.

2.3.5 Emerging Materials

The most cited materials that are rising in recent are mainly, as previously mentioned, materials used for their lightweight properties such as light alloys (e.g., aluminum, magnesium, and titanium alloys), high strength steel (HSS) family (e.g., conventional HSSs and AHSSs), composites (e.g., carbon fiber reinforced plastics or CFRP) and advanced materials.
Light alloys can be present in various components of the vehicle:

- Aluminum can be present in many components such as shock absorbers, wheel rims, rotor and seat frames. A dynamic material flow analysis model developed by Billy and Müller (2023), shows the effect of such material on emissions and scrap production. The increased adoption of wrought aluminium due to EVs poses problems on recycling since wrought aluminum requires low levels of impurities in respect to post-consumer waste. As reported by European Aluminium (2023) while aluminium recovery from ELVs is already at 95%, improvements can be made on the quality of the aluminium fraction recovered from ELVs, especially in separating the aluminium fraction into aluminium fractions of the same alloy family.
- Magnesium is the lightest structural automotive alloy with a density of 1.74 g/cm^3 (Zhang and Xu, 2022). It’s used in parts such as the powertrain system, transmission and body components. Mixing such material with aluminum or rare earth elements enhance its strength durability and corrosion resistance but its high price and limitation in high-temperature performance suggests room for improvement in its current application for the automotive sector.
- Titanium shows high corrosion resistance and elevated temperature performance. It has been used in components such as connecting rod, intake and exhaust valves and muffler. Similarly to magnesium, the high costs for extraction and processing may pose challenges in the extensive utilization of titanium alloys in the automotive industry.

High-Strength Steels (HSS) and Advanced High-Strength Steels (AHSS) are instead used due to their higher strength in respect to normal steel and can be therefore helpful in structural component and safety critical parts such as bumpers and impact beams. The presence of deformation and defects still pose issues in adopting these materials also in other components suggesting the need for further improvements on formability.

Composites like carbon fiber reinforced plastics offer a stronger option with higher energy absorption capability, while maintaining lightness, in respect to normal plastic. They can be used in parts such as bumpers, body panels but also suspensions and other accessories. Regarding the environmental impact, landfill and incineration should be avoided to ensure that these composites are recycled properly. Future challenges found by Giorgini et. Al (2020), includes the need of improved technology readiness as well as the assessment of scalability. The pyrolis process was identified as a viable and sustainable option the CFRP recycling process.

The high variety of materials and components in vehicles represents a viable option in the supply of raw material. Such products are becoming increasingly important for urban mining, where resources are extracted from used products rather than traditional mining, supporting the circular economy by reusing and recycling materials.

3. Regulatory Framework

3.1. The ELV Directive

As vehicles reach the end of their life cycle, their disposal poses significant environmental and resource management challenges. To address these issues, policymakers have developed frameworks to promote sustainability and circularity within the automotive sector. Among these, Directive 2000/53/EC, also known as the End-of-Life Vehicles (ELV) Directive stands out as an important directive in Europe, setting ambitious goals to minimize waste, enhance recycling, and reduce the environmental footprint of the industry.

Understanding the historical background, objectives, and achievements of this directive provides valuable insight into the broader efforts toward sustainable resource use and the transition to a circular economy in the automotive sector.

3.1.1 Structure and Key Chapters

The ELV Directive, proposed in 1997 and implemented in 2000, was created to harmonize the measures taken at national level regarding ELVs and waste, at the time between 8 and 9 million tons, that were yearly arising from such products.

As mentioned in Directive 75/442/EEC, an ELV is a considered waste when "the holder (owner) disposes of them or is obligated to do so under national law". The Directive applies to M_1 (vehicles used for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat) and N_1 (vehicles used for the carriage of goods and having a maximum weight not exceeding 3-5 metric tons) vehicles as well as three wheel motor vehicles.

The Directive main focus is on:

- **Art. 4 - Prevention**: promoting the reduction of waste from the design phase by encouraging vehicle manufacturers to limit hazardous substances, design for easier dismantling and recycling, and increase the use of recycled materials. It also sets requirements for vehicles to be free from certain hazardous substances (lead, mercury, cadmium, and hexavalent chromium) starting in July 2003 and mandates regular updates to these provisions.
- **Art. 5 - Collection**: Member States are required to establish systems for the collection of all ELVs and used parts from vehicle repairs, ensuring the availability of sufficient collection facilities. ELVs must be transferred to authorized treatment facilities (ATFs), and the presentation of a certificate of destruction (CoD) is necessary for deregistration. The last holder or owner should not incur any cost for delivering the ELV to an authorized treatment facility, with producers responsible for covering a significant portion of the costs. However, if an ELV lacks essential components or contains added waste, the delivery may not be fully free of charge.
- **Art. 6 - Treatment**: Member States are required to ensure that ELVs are stored and treated in compliance with the general requirements of the Directive 75/442/EEC and the technical standards in Annex I of this Directive, while also considering national health and environmental regulations. Furthermore, establishments must follow specific obligations, such as stripping vehicles before further treatment to minimize environmental impact, removing hazardous materials to prevent contamination, and ensuring that components are suitable for reuse or recycling.

- **Art. 7 - Reuse and Recovery**: Member States must take measures to encourage the reuse of components suitable for reuse, recovery of components that cannot be reused, and prioritize recycling when environmentally feasible. However, these actions should not compromise vehicle safety or environmental standards, such as emissions and noise control. Additionally, Member States are required to ensure that economic operators meet certain targets for reuse, recovery, and recycling of (ELVs):
    - By January 1, 2006, the reuse and recovery of ELVs must reach a minimum of 85% by average weight per vehicle annually, with a minimum of 80% for reuse and recycling. For vehicles produced before January 1980, lower targets may apply (75% for reuse and recovery, 70% for reuse and recycling), but reasons must be provided to the Commission and other Member States.
    - By January 1, 2015, these targets must increase to 95% for reuse and recovery and 85% for reuse and recycling.
- **Art. 8 - Coding Standards/Dismantling Information**: Member States must ensure that producers, in collaboration with material and equipment manufacturers, use coding standards for vehicle components to help identify those suitable for reuse and recovery. Producers must provide dismantling information for each new vehicle within six months of it entering the market. This information should help treatment facilities identify components, materials, and hazardous substances to meet recycling and recovery goals.
- **Art. 9 - Reporting and Information**: Every three years, Member States must report to the Commission on the implementation of this Directive. The report will include information on changes in the vehicle industry, treatment methods, and any potential distortions in competition. Member States must also require economic operators to publish information on vehicle design for recoverability and recyclability, the environmentally sound treatment of end-of-life vehicles (including fluid removal and dismantling), methods for reusing and recycling components, and progress in increasing recovery and recycling rates.

Annexes I and II, regarding respectively the “Minimum technical requirements for treatment” and “Materials and components exempt from Article 4(2)(a), provide additional details regarding the sites for the storage of ELVs pre-treatment, the sites for the treatment, the depollution phase which includes the removal of batteries and liquified gas tanks, neutralization of potential explosive components, (e.g. air bags), removal and separate collection and storage of several fluids, and the removal, as far as feasible, of all components identified as containing mercury.

Additional operations to promote recycling such as removal or catalysts, glass, metal components containing copper, aluminium and magnesium, tyres and large plastic components are also part of the Directive.

Therefore, the main parts and material targeted by the Directive are summarized as follow:

Targeted part / material	Key Measures	Directive Reference
Hazardous substances	Vehicle manufacturers shall limit and reduce Remove from ELVs and segregated	Art. 4.1(a)

Lead, mercury, cadmium, hexavalent chromium	Ban on vehicle put on the market after 1 July 2003 Stripped before further treatment on ELV	Art. 4.2(a)
Batteries and liquified gas tanks	Removed and appropriately stored	Annex I (2 & 3)
ELV fluids (fuel, oils, cooling liquids, etc.)	Removed and appropriately stored	Annex I (2 & 3)
Potential explosive components (e.g. air bags)	Removed or neutralized	Annex I (3)
Catalyst	Removed	Annex I (4)
Metal components containing copper, aluminium and magnesium	Removed if not segregated prior to shredding	Annex I (4)
Tyres	Removed and appropriately stored	Annex I (4)
Large plastic components (bumpers, dashboard, fluid containers, etc.)	Removed if not segregated in a manner that allows effective recycling	Annex I (4)
Glass	Removed	Annex I (4)

Table 1. Summary of main parts and material regulated by the ELV Directive)
(Source: personal summary of the articles from Directive 2000/53/EC)

Additionally, the concepts of reuse, recycling, and recovery are introduced with specific targets outlined in Article 7 of the ELV Directive, where:

- **Reuse**: Any operation by which components of end-of-life vehicles (ELVs) are used for the same purpose for which they were originally designed, without significant modification.
- **Recycling**: The reprocessing of waste materials into new products, either for their original purpose or for other purposes, excluding energy recovery (i.e., the use of combustible waste to generate energy through direct incineration).
- **Recovery**: Any operation aimed at extracting materials or energy from waste, including both recycling and energy recovery, such as using non-recyclable parts of vehicles for energy production or material recovery through processes like combustion or mechanical treatment.

With articles covering areas from the collection of the vehicles, to the treatment and 3Rs rate targets, the Directive was the first attempt to regulate the criticality of such products to ensure their proper disposal at EoL. While many articles present a general overview without detailed targets, such as the introduction of the design for dismantlability and the introduction of recycle content in vehicles (RC), the Directive was important for establishing the framework for the European countries.

3.1.2 3Rs rates in European Countries

The graph below illustrates the reported percentages for the 3Rs across the 27 European countries (from 2020), highlighting the reference for Recycling, Reuse, and Recovery. During the reported period, Recycling and Reuse exceeded the Directive's targets, while Recovery and Reuse struggled to meet the 95% target.

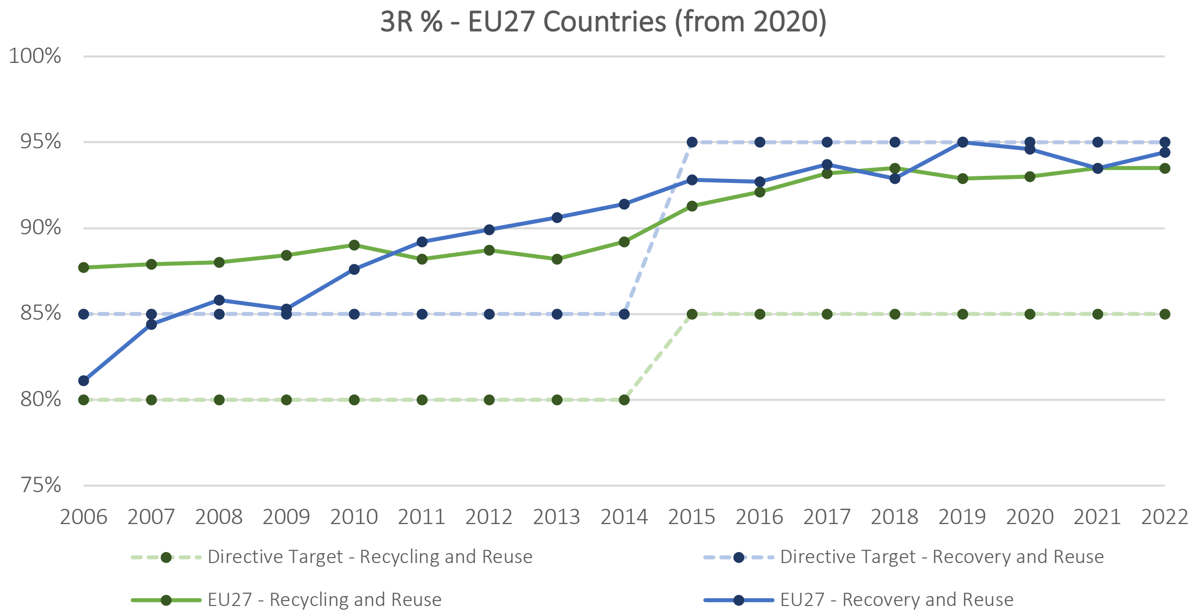

Figure 3. Reuse, recycling and recovery rates on average for EU27 countries
(Source: personal elaboration of data from End-of-life vehicles - reuse, recycling and recovery, totals [env_waselvt] by Eurostat)

Looking at the 2022 Eurostat data for the 27 countries, it is evident that the Recycling and Reuse target was missed by only two countries, a notable improvement compared to six in 2015. In contrast, the Recovery and Reuse target was missed by ten countries, though this is an improvement over the eleven countries in 2015.

The lowest reported value came from Malta, with 84.1%. Compared to 2015, the year when the new targets were implemented, six countries experienced a decrease in their recycling and reuse rates, while seven countries saw a drop in their recovery and reuse rates. Data for Lithuania and Romania was not reported for 2022.

An interesting anomaly is the presence of values above 100% for Czechia, with reported rates of 117.2% and 121.8% respectively. This discrepancy can be attributed to several factors:

- **Time Lag in ELV Processing**: ELVs may be reported in one year but processed in subsequent years, leading to discrepancies in recovery and recycling rates.
- **Storage of ELVs**: dismantlers may delay processing ELVs when metal prices are low, as was the case in Greece in 2015. Additionally, incentive programs like Germany's 2009 vehicle scrapping initiative led to an influx of vehicles that exceeded dismantling capacity. The storage and later processing of these vehicles contributed to recovery rates exceeding 100%.
- **Different methodological approaches**: the methods for monitoring reuse, recovery, and recycling can vary. The most accurate approach is reporting based on data from ATF operators, detailing the amounts of reused, recycled, and recovered materials arising from depollution, dismantling, and shredding operations. Alternatively, some countries use the "metal content assumption" (MCA) approach, where the metal content of vehicles is estimated, regardless of whether metals are separated during de-pollution and dismantling, shredding, or whether metals are exported.

These discrepancies underline the challenges in ensuring accurate and comparable reporting across member states and emphasize the need for harmonized methodologies and consistent monitoring to meet the ambitious targets set by the ELV Directive.

The table below provides a comparative summary of the EU27 countries in year 2015 and 2022, highlighting the 3R percentages reported by each country that did not meet the target set by the Directive. It also emphasizes the countries that reported a decrease in their percentages, indicating difficulties in maintaining the rates achieved in 2015.

	Recycling and Reuse			Recovery and Reuse		
Country	2015	2022	Δ %	2015	2022	Δ %
Belgium	91,3%	93,5%	2,2%	96,7%	97,7%	1,0%
Bulgaria	94,4%	94,8%	0,4%	95,1%	95,1%	0,0%
Czechia	90,2%	117,2%	27,0%	95,7%	121,8%	26,1%
Denmark	91,2%	85,5%	**-5,7%**	97,6%	94,6%	**-3,0%**
Germany	87,7%	86,4%	**-1,3%**	95,8%	93,7%	**-2,1%**
Estonia	86,0%	85,3%	**-0,7%**	87,0%	91,5%	4,5%
Ireland	83,3%	88,5%	5,2%	91,8%	95,5%	3,7%
Greece	64,5%	83,5%	19,0%	68,9%	88,5%	19,6%
Spain	85,0%	86,4%	1,4%	95,0%	93,1%	**-1,9%**
France	87,5%	88,3%	0,8%	94,3%	95,6%	1,3%
Croatia	92,8%	96,9%	4,1%	99,5%	97,1%	**-2,4%**
Italy	84,6%	86,0%	1,4%	84,7%	86,0%	1,3%
Cyprus	89,1%	90,6%	1,5%	90,7%	99,1%	8,4%
Latvia	86,6%	91,2%	4,6%	87,0%	91,2%	4,2%
Lithuania	94,6%	-	-	95,0%	-	-
Luxembourg	87,0%	96,9%	9,9%	97,0%	97,9%	0,9%
Hungary	94,6%	96,8%	2,2%	95,2%	97,5%	2,3%
Malta	77,7%	84,1%	6,4%	77,7%	84,1%	6,4%
Netherlands	87,7%	87,2%	**-0,5%**	97,0%	98,7%	1,7%
Austria	86,9%	85,9%	**-1,0%**	96,9%	97,4%	0,5%
Poland	94,7%	95,3%	0,6%	97,0%	97,7%	0,7%
Portugal	84,0%	89,1%	5,1%	92,7%	92,2%	**-0,5%**
Romania	85,1%	-	-	90,8%	-	-
Slovenia	90,2%	86,7%	**-3,5%**	95,6%	93,1%	**-2,5%**
Slovakia	88,4%	95,9%	7,5%	89,4%	97,1%	7,7%
Finland	82,8%	84,7%	1,9%	97,3%	95,2%	**-2,1%**
Sweden	84,6%	87,0%	2,4%	96,8%	97,6%	0,8%

Table 2. Comparison of rates reported in 2015 vs. 2022 for European Countries (Source: personal elaboration of data from End-of-life vehicles - reuse, recycling and recovery, totals [env_waselvt] by Eurostat by highlighting the decreases in the recovery rates)

The ELV Directive, with its 13 articles and 2 annexes, laid the groundwork for European countries by highlighting the importance of addressing ELVs, their materials, and their treatment. It marked a significant step in shifting responsibility not only to ATFs, which handle vehicles at the end of their life, but also to producers.

By discouraging the use of hazardous materials and emphasizing vehicle dismantlability, the Directive moved beyond considering vehicles solely at the assembly stage. Instead, it brought attention to the need for facilitating the dismantling and identification of parts and components, a crucial factor in ensuring efficient recovery processes at the end of a vehicle's life.

3.2. Transition to the ELV Regulation

3.2.1 Transition from Directive to Regulation

In July 2023, a new regulation was proposed following a review of Directive 2000/53/EC on end-of-life vehicles (ELV Directive) and Directive 2005/64/EC on the type-approval of motor vehicles with regard to their reusability, recyclability, and recoverability ("3R type-approval" Directive).
The proposal aims to facilitate the transition of the automotive sector to a circular economy by reducing the environmental footprint linked to vehicle production and EoL treatment, strengthening the sustainability of the automotive and recycling industry in Europe, and addressing the increasing use of critical raw materials and plastics.

3.2.1 Structure and Key Chapters

The ELV Directive, while focusing on several issues related to the correct management of ELVs, is, per legislative definition, an instrument that is then translated into the various countries differently and therefor the implementation in this form can create differences in the treatment of the resources.

By creating a Regulation that replaces the ELV and 3Rs Directives and amends the Regulation related to approval and market surveillance of vehicles (Regulation (EU) 2018/858 and Regulation 2019/1020), the first objective is to harmonize the treatment of ELVs at European level.

The proposed Regulation, summarized in the table below, is composed of several chapters (from I to IX), with chapter IV divided into 4 sections, and present overall 57 articles, a number much higher than the one presented in the ELV Directive, highlighting the increased scope and level of detail of this legislation.

Chapter	n. of articles
CHAPTER I - GENERAL PROVISIONS	From art. 1 to 3
CHAPTER II - CIRCULARITY REQUIREMENTS	From art. 4 to 7
CHAPTER III - OBLIGATIONS OF MANUFACTURERS	From art. 8 to 13
CHAPTER IV - MANAGEMENT OF END-OF-LIFE OF VEHICLES	From art. 14 to 36
CHAPTER V - USED VEHICLES AND THEIR EXPORT	From art. 37 to 45
CHAPTER VI - ENFORCEMENT	From art. 46 to 49
CHAPTER VII - DELEGATED POWERS AND COMMITTEE PROCEDURE	From art. 50 to 52
CHAPTER VIII - AMENDMENTS	From art. 53 to 54
CHAPTER IX - FINAL PROVISIONS	From art. 55 to 57

Table 3. Structure of the proposed ELV Regulation
(Source: reporting of chapter titles and article from the proposed ELV Regulaion)

Article 2 outlines the scope of the ELV Regulation, initially applying to vehicles in categories M1 and N1, and later extending to M2, M3, N2, N3, and O vehicles after five years. However, not all provisions of the regulation apply to these larger vehicle categories, with certain articles excluding them, particularly those related to reusability and recyclability.

Regarding the Circularity Requirements, the regulation focuses on:

- **Art. 4 - Reusability, recyclability and recoverability** of vehicles: maintain the reuse, recycling and recovery targets set in the past for vehicles approved under Regulation (EU) 2018/858, which must meet the targets 72 months after the regulation comes into force. Manufacturers must collect and verify material data to calculate these rates using a Commission-adopted methodology or ISO standards until then. Parts must be labelled according to Annex VI, including specific requirements for e-drive motors. Additionally, components listed in Part E of Annex VII, such as airbags and emission systems, must not be reused in new vehicles.
- **Art. 5 - Requirements for substances** in vehicles: the presence of lead, mercury, cadmium, and hexavalent chromium in vehicles is banned, except for specific exemptions where use is unavoidable, no alternatives exist, and socio-economic benefits outweigh risks.
- **Art. 6 - Minimum recycled content** in vehicles: a minimum recycled content (RC) in vehicles, 72 months after the entry into force of the regulation, is added, which aligns with the broader strategy of the European Commission to increase the presence of recycled material into products. In the case of vehicles, the request is to reach a minimum of 25 % of plastic recycled by weight from post-consumer plastic waste, 25% of which must come from ELVs, therefor reaching 6,25%.
- **Art.7 - Design to enable removal and replacement**: vehicles, 72 months after the entry into force of the regulation, must be designed to allow authorized treatment facilities to easily remove specified parts during the waste phase, with a particular focus on electric vehicle batteries and e-drive motors, which must be removable non-destructively during both the use and waste phases; the Commission may update the list of parts for removal and adopt implementing acts for harmonized implementation.

Regarding the obligations for the manufacturers, several articles are also adopted:

- **Art. 9 - Circularity strategy**: the manufacturer must create a circularity strategy, for vehicle types approved 36 months after the regulation enters into force, detailing actions to meet circularity requirements, submit it to the Commission within 30 days of type-approval, and update it every five years. The Commission will make these strategies public (excluding confidential information) and is authorized to adjust requirements based on technological, scientific, market, and regulatory progress. Additionally, the Commission will publish a report on the automotive sector's circularity every six years.
- **Art. 10 - Declaration on Recycled Content Present in Vehicles**: manufacturers must declare the share of RC in specific materials (neodymium, dysprosium, praseodymium, terbium, samarium, boron, aluminium, magnesium, and steel) for each vehicle type type-approved after a certain date. The declaration must indicate whether the material is recycled from pre-consumer or post-consumer waste.
- **Art. 11 - Information on Removal and Replacement of Parts, Components, and Materials Present in Vehicles**: manufacturers must provide waste management and repair operators with unrestricted, standardized access to information for safely removing and replacing key vehicle parts, such as electric vehicle batteries, e-drive motors, fluids, critical raw materials, and digitally coded components. This

information must be kept up-to-date and provided free of charge, although manufacturers may charge for administrative costs.

- **Art. 12 - Labelling of Parts, Components, and Materials Present in Vehicles**: manufacturers and their suppliers must use standardized coding for labeling vehicle parts and materials, as specified in Annex VI. E-drive motors containing permanent magnets must display a clear, permanent label with specific information.
- **Art. 13 - Circularity Vehicle Passport**: 84 months after the regulation's entry into force, every vehicle must have a circularity vehicle passport containing the information in Article 11 in digital format, accessible for free. The manufacturer is responsible for ensuring the passport's accuracy and currency. The passport must adhere to open standards and be interoperable. Once a vehicle becomes an ELV, the passport will expire 6 months after the certificate of destruction is issued.

The chapter related to the management of ELVs mainly focuses on:

- **Art. 16 - Extended Producer Responsibility**: From 36 months after the regulation's entry into force, producers must ensure the extended producer responsibility for vehicles they place on the market in a Member State. This includes ensuring that ELVs are collected (Art. 23), treated (Art. 27), and that waste management operators meet the targets in Art. 34
- **Art. 20 - Financial Responsibility of Producers**: Producers must pay financial contributions to cover costs related to ELVs, including collection, treatment, awareness campaigns, notification systems, and reporting. These costs are not covered by waste management operator revenues from spare parts, depollution, or recycled materials. Producers fulfilling their obligations individually must provide a guarantee to cover costs for vehicles they place on the market, with the amount determined by the Member State. This guarantee may be in the form of participation in financing schemes, insurance, or a blocked bank account.
- **Art. 24 - Delivery of end-of-life vehicles to authorised treatment facilities**: all ELVs must be delivered to ATFs. The delivery must be free of charge for the last vehicle owner, unless the ELV is missing essential parts (except for the electric vehicle battery) or contains waste added to the vehicle.
- **Art. 27 - Obligations for authorised treatment facilities**: ATFs must accept and treat all ELVs, their parts, components, materials, and waste parts from vehicle repairs in compliance with their permits and this regulation. They must ensure treatment meets the conditions specified in Articles 28-31, 34-35, and Annex VII, and use best available techniques. These facilities must store, depollute, remove specific parts, and treat vehicles following the waste hierarchy and relevant regulations.
- **Art. 29 - Depollution of end-of-life vehicles**: ATFs must depollute ELVs as soon as possible after delivery, following the minimum requirements set out in Annex VII. Fluids and liquids, such as waste oils, must be separately collected and stored, with waste oils treated in accordance with Directive 2008/98/EC. Parts containing hazardous substances must be removed and handled as per Directive 2008/98/EC. Batteries should be removed and stored for further treatment under the Batteries Regulation. Depolluted parts, components, and materials must be handled and labelled according to specific regulations. The depollution process must be documented by recording the required information.

- **Art. 30 - Mandatory removal of parts and components for reuse and recycling prior to shredding**: ATFs must remove parts and components listed in Part C of Annex VII from ELVs prior to shredding, after the depollution process. However, this requirement does not apply if the facility demonstrates that post-shredder technologies can separate materials from parts and components listed in entries 13-19 of Part C as efficiently as manual dismantling or semi-automated disassembly.
- **Art. 34 - Reuse, Recycling, and Recovery Targets**: Member States must ensure that, from 36 months after the Regulation's entry into force, waste management operators meet annual targets of 95% reuse and recovery (excluding batteries) and 85% reuse and recycling (excluding batteries) by average weight per vehicle; and from 60 months, achieve a yearly recycling target of at least 30% for plastics by weight.
- **Art. 35 - Ban on Landfilling of Non-Inert Waste**: from 36 months after the Regulation's entry into force, fractions from shredded ELVs containing non-inert waste, not processed by post-shredder technology, shall not be accepted in a landfill.

The remaining chapters focuses on aspects of ELVs related to its exports, how Member States shall monitor and enforce the proposed Regulation, and the amendments made through this legislation.

Several annexes are also attached to the new regulation:

- **Ann. I - Criteria for determination whether a used vehicle is an ELV**: list of the conditions to determine whether a vehicle can be considered technically irreparable, economically irreparable and additional criteria to determine if the vehicle can be considered ELV
- **Ann. II - Calculation of the rates of reusability, recyclability and recoverability**: a reference vehicle, the most challenging version of a model for recycling, is selected with regulatory approval. The manufacturer assesses material composition, ensuring calculations follow standardized rounding rules. Components must be removable non-destructively to count as reusable, while certain parts (listed in Annex VII) are always considered 0% reusable but fully recyclable and recoverable.
- **Ann. III - Conditions and maximum concentration values for the presence of substances**: this annex establishes the maximum allowable concentration of hazardous substances in vehicle materials, setting a limit of 0.1% by weight for lead, hexavalent chromium, and mercury, and 0.01% for cadmium. It also provides exemptions for certain spare parts placed on the market after July 1, 2003, if they are used in vehicles introduced before that date, except for specific components like wheel balance weights, carbon brushes for electric motors, and brake linings.
- **Annex IV - Circularity strategy:** This annex outlines the key elements of a manufacturer's circularity strategy to ensure vehicles comply with legal requirements on sustainability throughout their production. It includes non-technical descriptions of actions taken to maintain compliance, data collection and verification processes, and assumptions about EoL treatment technologies. Manufacturers must also provide details on recycled content in vehicles and commit to actions that improve dismantling, recycling technologies, and material reuse.
- **Annex V - Information Requirements on Removal and Replacement**: this annex mandates manufacturers to provide detailed data on the number, location, weight, and removal procedures for electric vehicle batteries, e-drive motors, and specific

components listed in Annex VII. It specifies the need for technical instructions on discharging, fastening, sealing, and required tools for removal and replacement. Additionally, it covers digitally coded components, requiring information on software activation, interchangeability, and manufacturer support, ensuring safe and efficient dismantling processes.

- **Annex VI - Labelling Requirements**: This annex establishes labelling standards for vehicle materials, requiring plastic parts over 100 grams and elastomer parts over 200 grams to be marked according to ISO standards. It also mandates specific labelling for e-drive motors containing permanent magnets, including material type, manufacturer details, and a data carrier with removal instructions. These requirements aim to enhance material identification and facilitate recycling and recovery processes.
- **Annex VII - Treatment Requirements**: this annex outlines the mandatory procedures for the storage, depollution, dismantling, and post-processing of ELVs to enhance sustainability and material recovery.
    - **Part A and B (Storage, Depollution, and Dismantling)**: ELV treatment facilities must ensure that hazardous fluids are fully drained before shredding, with a focus on hazardous substances (e.g., mercury, PFAS). Proper storage and management of these fluids are mandatory to prevent contamination.
    - **Part C (Mandatory Removal of Components and Exemptions)**: key parts that must be removed and separated for reuse or recycling before shredding. Exemptions are possible if with the use of post-shredding technologies they can demonstrate that the quality and quantity of recovered materials are comparable to the separately removed parts.
    - **Part D (Reuse, Remanufacturing & Refurbishment)**: parts intended for reuse or remanufacturing must be evaluated for functionality, completeness, and damage. They must also be labeled with their VIN, dismantler info, and part name for traceability.
    - **Part E (Components Not to Be Reused)**: safety-critical components like airbags, catalytic converters, and seat belts must not be reused due to safety concerns.
    - **Part F (Specific Treatment):**
        - SLI & EV batteries must be treated according to the EU Batteries Regulation.
        - E-drive motor materials, such as neodymium magnets, must be removed and recycled where possible.

Additionally, other annexes provide further details on specific requirements such as the registration of producers and the information to be included in the Certificate of Destruction (CoD), ensuring proper documentation and compliance throughout the vehicle disposal process.

Overall the Regulation, by setting new targets and by increasing the scope of the Directive, is regulating the ELV management supply chain by shifting even more the responsibility on OEMs regarding the vehicles that put into the market, the information related to them and presence of recycled content, while also increasing the requests to ATFs regarding the parts and material that needs to be recover already at dismantling stage to increase the purity of the materials that can be extracted when recycling, therefor addressing the issues of down-cycling that arises when a low purity is achieved.

3.2.1 Key Changes and Expected Outcomes

While the ELV Directive is already covering most of the articles proposed in the Regulation, the level of details and targets is now much clearer and permits also to manage more easily some of the current issues of the ELV management such as the presence of recycle content in vehicle, the role of the OEMs in the design of vehicles and as financial contributor in the supply chain but also on the manual removal of parts, points that were already mentioned in the Directive but that now present clearer articles related to them.

While in the Directive the presence of recycle content was just encouraged, in the new regulation is now one of the most important articles, setting 25% of recycle content for plastic from post-consumer sources and linking also part of that percentages to ELVs, therefor addressing the current lack of recycle content in vehicles, especially coming from ELVs.

OEMs will therefor become important actors in the overall demand of recycle plastic and they will be then forced to solve the issues that may arise in the use of recycle plastic in the car especially when considering that plastic is present both in the internal and external parts of the car and therefor different functional requirements are set depending on the area of use of the material.

The overall objective of the Commission is to increase the recycle content also for other materials and therefor OEMs will be asked to also focus on adding recycled steel in their car and based on the path followed by the Commission, the same request could be expanded to other materials such as aluminum.

It’s therefore important for OEMs to assess the issues in the use of recycled materials and to evaluate suppliers that will be asked to manufacture parts with a certain % of recycle content in the future, based on the parts targeted by the OEM, to reach the 25% requested by the Regulation.

When considering the share of recycle content coming from ELVs, which is set at 6,25% for plastic, it’s important to consider that a 1:1 relation may not apply when considering the vehicles of the past with those of the present. Older vehicles contain a lower presence of plastic and therefor recover just the 6,25% of the plastic from those vehicles will not be enough to cover the demand of the future.

Additionally, inefficiency in the recovery of plastic from ELVs as well as at shredding and recycling stages contributes in increasing the material that needs to be recovered to fulfill the 6,25% request from the Regulation.

This will indeed positively impact the amount of plastic that is recovered from ELVs instead of being left on the vehicle and therefor shredded together with also the rest of the carcass, therefore positively affecting the purity of the materials that come from ELVs.

Also, the role of OEMs regarding the design of parts is in the Regulation described in a more precise way. While in the Directive the design was mentioned to “facilitate the dismantling, reuse and recovery” it now takes an entire Article in the Regulation (Art. 7 - Design to enable removal and replacement of certain parts and components in vehicles) and it focuses on enabling the removal of parts, listed in the Annex, by ATFs.

It also mentions the role of joining, fastening and sealing elements to enable the removal of EV batteries and e-motors in a non-destructive manner which positively affects the operations or repair and maintenance as well as the recovery of parts at EoL. While currently no specific rules are set for the design of dismantlability, the Commission has the power to establish detailed conditions to ensure a uniform implementation of removal and replacement requirements.

While design can indeed ease the dismantling of the vehicle's parts and components, it's also important to highlight that the requirements coming from the Regulation will be assessed with a lag that could take even 17 years, considering an average time to market for vehicle of 5 years and an average life around 12 years.

It is therefore important to keep ATFs informed also on the vehicles currently in circulation regarding the positions of key parts and components, their composition and way to remove. OEMs should in fact share information with ATFs.

While IDIS (International Dismantling Information System) is a well-known instrument for ATFs to access data for quick dismantling of vehicles, a stakeholder interviews held by the European Commission highlighted the current problems of such system, from the level of details that is not always enough to carry out the dismantling activities as well as the lack of information for some models.

While the possibility to access others database such as RMI for repair and maintenance information is present, ATFs highlight the issues in having to check multiple systems to gather the necessary data about the vehicle and also the costs related in adopting other systems. The Regulation therefore propose a Circularity Vehicle Passport for vehicles containing the information request by Article 11 related to "Information on Removal and Replacement of Parts, Components, and Materials Present in Vehicles".

While this instrument mitigates the issues related to the level and quantity of information related to vehicles, it does not solve the issue of vehicles already in circulation that do not have a passport. Due to the presence of a large number of manufacturers, IDIS still remains a valid option to collect the information needed by ATFs to properly dismantle vehicles but it also highlights the need for a more unified and standardized system that can streamline the process and ensure that all necessary data is easily accessible by ATFs.

While this is addressed in Article 11, the Regulation doesn't specify any communication platform or methodology for sharing the standardized data regarding the vehicle. It is therefore left to OEMs to find a way to communicate the data and also the level of details that needs to be provided to ATFs.

Additionally, the number of components removed from the vehicle during dismantling is set at 19 in the Regulation with parts including electric and electronic components such as inverters of the electric vehicles, printed circuit boards with a surface area larger than 10 cm^2, photo-voltaic (PV) panels with a surface area larger than 0.2 m^2 and control modules and valve boxes for the automatic transmission, which are difficult to be identified by the ATF especially considering that only components with a specific surface area will be asked to be removed.

Even for more common parts such as the dashboard and wire harness, the information shared by the OEM needs to cover not only the position in the vehicle but also the most efficient way to dismantle such parts, which are often connected with other parts and components of the vehicle and their complete removal, with incomplete information, will increase the dismantling time needed.

3.3. Other Relevant Directives and Regulations and their connections to ELVs

3.3.1 New Batteries Regulation (2023/1542)

Due to the importance of batteries in the transition towards climate neutrality and their vast use in everyday life products, among which vehicle have seen an increasing use, the Batteries Directive will be repealed in 2025 by the new Batteries Regulation.

Due to the increased use of batteries in EVs it’s important to set sustainability requirements and limitations on hazardous substances present as well as providing the complete carbon footprint from material extraction to disposal: while batteries help in reducing the emissions related to the use phase, they still have emissions related to the other part of their lifecycle.

Therefor the new Regulation sets a mandatory carbon footprint declaration (Art. 7) also for EVs batteries as well as bear a label that indicates their carbon footprint and performance class. In addition to labeling, a maximum life cycle carbon footprint threshold will be introduced, starting with electric vehicle batteries in 2028.

Much like for plastic in the ELV Regulation, from 2031 specific minimum RC target are also set for batteries which will then increase by 2036.

Data about the state of health and expected lifetime will be included in battery management system (BMS) (Art. 14) therefore facilitating the evaluation of the re-use or repurpose of the battery by operators.

Regarding waste, article 61 establishes the obligation for producers of SLI batteries, industrial batteries, and electric vehicle batteries to take back waste batteries free of charge and ensure their separate collection, regardless of type, condition, or origin. Collection must be organized through take-back systems in collaboration with distributors, remanufacturers, ELV treatment facilities, and public waste management entities.

Additionally, operators of treatment facilities handling ELVs or waste electrical and electronic equipment (WEEE) to handover waste batteries to producers, producer responsibility organizations or selected waste management operators (Art. 65).

Regarding their treatment (art. 70), waste batteries must not be disposed of or used for energy recovery. Instead, they must be treated according to the requirements outlined in Annex XII. Treatment facilities must follow specific storage and safety measures, including removing all fluids and acids, storing batteries in suitable containers, and separating hazardous materials like mercury and cadmium. Lithium-based batteries also require special handling to prevent heat, water, and physical damage.

To align with the sustainability path followed by the European Commission, recycling targets are also set for batteries in Annex XII, impacting not only the different type of batteries (lead-acid, lithium-based, nickel-cadmium and other waste batteries) but also the various materials (cobalt, copper, lead, lithium and nickel).

Additionally, the digital battery passport is part of the Regulation and it’s detailed in chapter IX. With entry into force at the beginning of 2027, the passport will contain information accessible to various stakeholders such as the public, related bodies and market surveillance authorities and will contain both public and restricted information, including details essential for battery dismantling, safety measures, and recycling. It aims to support activities like repair, remanufacturing, and recycling, providing data such as battery composition and dismantling guidelines.

Due to the increasing presence of batteries in products and also in vehicles, the Batteries Regulation, with link to the ELV Directive and Regulation, helps in managing more accurately this type of products which contains critical raw materials that are important to be recovered once EoL is reached.

Therefore, the correct management of batteries once removed from ELVs, which is already mandatory from the ELV Directive, and the addition of a passport to also share the needed information for the related stakeholders, will facilitate their removal in a safe way and the possibility to reuse them if all safety and technical requirements are met.

While the addition of recycling targets will also help closing the loop, the route of reuse and remanufacturing are currently not easy to take due to risks that ELVs may be damaged and therefor the battery could be non-reusable. A study on vehicles' batteries repurposes (Al-Alawi et. Al, 2022) shows that repurposing Retired Electric Vehicle Battery (REVB) for second-life applications, especially in renewable energy systems, holds promise but faces challenges.

Most research has focused on stationary technologies, such as integrating REVB into solar-powered energy storage systems, showing potential for reduced grid dependence. However, repurposing for mobile applications or grid services remains financially and technically challenging due to accelerated degradation from intensive use.

Despite these challenges, enhancing battery management systems (BMS) and refining aging models could help unlock more widespread reuse, supporting a circular economy and extending the lifecycle of EV batteries.

3.3.2 Circular Economy Action Plan

The new Circular Economy Action Plan (CEAP) adopted by the European Commission in 2020, it's part of the European Green Deal and therefore an important block in the EU's 2050 climate neutrality target. The initiatives cover the entire lifecycle of products, from design to waste by making sure that resources are kept in the economy for as long as possible.

The EU's Circular Economy Action Plan (CEAP) provides a broad policy framework that is gradually reshaping product design and waste management across various sectors, including the automotive industry. One of the key elements of the CEAP is its focus on sustainable material use and recycling.

For instance, the plan calls for mandatory recycled content requirements for products such as packaging, construction materials, and vehicles. This means that vehicle manufacturers are increasingly encouraged to incorporate recycled plastics and metals into new vehicles, thereby reducing the reliance on virgin raw materials.

Such measures promote resource efficiency by ensuring that materials recovered from ELVs are effectively re-integrated into the manufacturing cycle. In this way, the CEAP is indirectly influencing vehicle design and the overall circularity of the automotive sector, aligning new vehicle production with the environmental goals of waste reduction and material recovery.

The CEAP also underscores the need for a modernized waste policy that supports waste prevention and circularity. Revisions to EU waste legislation are set to enhance waste management practices by setting clear targets for waste reduction and by promoting separate collection systems for key waste streams.

These measures are particularly relevant to the automotive industry because they establish the framework for the efficient dismantling and recycling of ELVs. Enhanced waste policies ensure that materials such as metals, plastics, and composites are recovered in a form that meets quality standards, thereby facilitating their reuse in new products.

Additionally, the focus on creating a toxic-free environment by minimizing hazardous substances in recycled materials is crucial for ELVs, where contaminants in secondary raw materials can compromise safety and performance. This holistic approach to waste management and recycling is essential to transform ELVs from being mere waste to becoming valuable sources of secondary raw materials.

On the economic and innovation fronts, the CEAP seeks to drive the transition toward a circular economy through targeted financial instruments and support for research and digitalization. The integration of circular economy objectives into EU financial frameworks, such as the EU Taxonomy Regulation and the Circular Economy Finance Support Platform, ensures that investments are directed toward sustainable practices.

Furthermore, the plan emphasizes the role of digital tools in achieving circular objectives. Digital product passports and resource mapping systems will enable stakeholders to track the entire lifecycle of vehicle components, providing crucial data that facilitates more efficient recycling and remanufacturing operations.

Such innovations not only streamline the ELV processing chain but also enhance the transparency and efficiency of the overall supply chain, paving the way for more sustainable automotive production practices.

Finally, the CEAP highlights the importance of global leadership in driving the transition to a sustainable, circular economy. By advocating for international cooperation and the establishment of global alliances, the EU aims to set common standards for resource efficiency and waste management that extend beyond its borders.

This global approach is particularly significant for the automotive industry, which operates within interconnected international supply chains. Harmonized standards and policies can facilitate cross-border trade in recycled materials and promote best practices in ELV recycling worldwide.

Such measures will ultimately support a more resource-efficient and climate-neutral automotive sector, where vehicles are designed not only for performance and safety but also for easy dismantling and high-quality recycling at the end of their life.

4. ELV Supply Chain and Current Practices

4.1. Processes and End-of-Life Pathways

4.1.1 Stages: Sourcing, Dismantling, Part Reuse, Shredding, Recycling

The ELV dismantling process consists of several key stages, each serving a distinct purpose in the management and recovery of vehicle materials:

- Sourcing: a vehicle is classified as ELV when it's no longer suitable for use due to natural wear and tear, severe damage that makes repairs technically unfeasible (technical loss vehicle), or when repair costs exceed the vehicle's residual value (economic loss vehicle). The condition of an ELV varies significantly: older vehicles may be structurally intact but have worn-out parts that are harder to reuse, while accident-damaged vehicles can be more challenging to dismantle but may contain salvageable components with high resale value. ELVs can reach an Authorized Treatment Facility (ATF) through direct customer disposal, insurance claims, dealership returns, or auctions. Once at the ATF site, a Certificate of Destruction (CoD) is issued, allowing the vehicle to proceed to the next phase.
- Depollution: in compliance with the ELV Directive, depollution is a mandatory step in which hazardous materials and fluids are safely extracted from the vehicle. Common depollution activities include the removal or neutralization of airbags, the extraction of fuels, coolants, and oils, as well as the removal of batteries and other potentially harmful components.
- Dismantling: after depollution, the ATF proceeds with dismantling the vehicle to recover parts and material. The extent of dismantling depends on various factors, such as the ATF's capabilities and knowledge, the condition of the vehicle, and the market demand for second-hand components. Parts with high resale potential are removed and labeled for traceability before being sold to private buyers or professionals. Components and materials with a recycling value that exceed costs are also extracted and stored separately. The remaining vehicle structure, once stripped of reusable and high-value components, is typically compressed using a car crusher to facilitate transportation before being sold to shredders at scrap steel prices.
- Storing and marketing of parts and material: vehicles are composed of numerous parts and components, each with a different demand on the market. The greater the logistics and operational capabilities of the ATF, the higher the profit potential from the second-hand market. Online marketplaces such as B-parts, and eBay have made the reuse route the preferred option for ATFs seeking higher profits due to the large usage of such platform for consumers. Additionally, ATFs may also use their own online marketplace or sells parts directly in their shops. Parts with lower demand or significant wear and tear typically follow the recycling and waste recovery route, which offers lower margins depending on the market prices set by recyclers and the costs involved in dismantling. For instance, exterior plastic parts like bumpers are easier to remove but may not yield enough revenue to cover the dismantling costs, while wire harnesses, which are often hidden beneath other components, may be more challenging to recover but can offer higher profits due to the value of copper. Consequently, ATFs must carefully evaluate a range of variables when deciding on the best course of action for each part.

- **Shredding**: once the vehicle's carcass reaches the shredder, it is broken down into smaller pieces using large machines, which facilitate the separation of remaining materials. Post-shredding technologies (PST) are then used to sort the materials, identifying ferrous metals, non-ferrous metals, and non-metallic components. However, the shredded residue, known as Automotive Shredder Residue (ASR), presents a significant challenge in recycling. ASR, which consists of a mix of plastic, rubber, and other non-metallic materials, is difficult to recycle due to its complex composition. Traditionally, ASR has been considered hazardous waste and sent to landfills. However, recent developments focus on finding more sustainable methods for treating ASR.
- **ASR Treatment and Disposal:** Several methods have been explored to better treat ASR and recover more materials, including:
    - Material recovery: Advanced technologies in post-shredding treatments (PSTs) can help separate valuable materials, such as plastics, from ASR for reuse.
    - Energy recovery: ASR has often been incinerated or used in co-combustion with cement kilns, although these methods raise environmental concerns due to emissions and hazardous residue.
    - Emerging technologies: Research into pyrolysis and gasification methods is ongoing, with the aim of recovering more materials from ASR. Though still in the evaluation stage, these technologies show promise for converting ASR into valuable products like oils, gases, or carbon.

  Given the EU's recycling and recovery targets, 85% for reuse and recycling and 95% for reuse and recovery from 2015, it's crucial that ASR treatment methods evolve to meet these goals. However, the economic viability of these methods remains a significant challenge, influenced by both regulatory frameworks and market conditions for recycled materials, which can impact profitability for ATFs and recyclers.
- **Recycling**: Following shredding, the recycling of materials, particularly ferrous and non-ferrous metals, proceeds with specialized treatments. While these materials are relatively easier to recycle, non-metallic materials such as ASR remain a persistent issue. Despite advances in technology, there is still considerable potential for improving the recovery of precious metals and plastics, which could provide higher economic returns.

A visual representation of the various processes is shown in Figure 4.

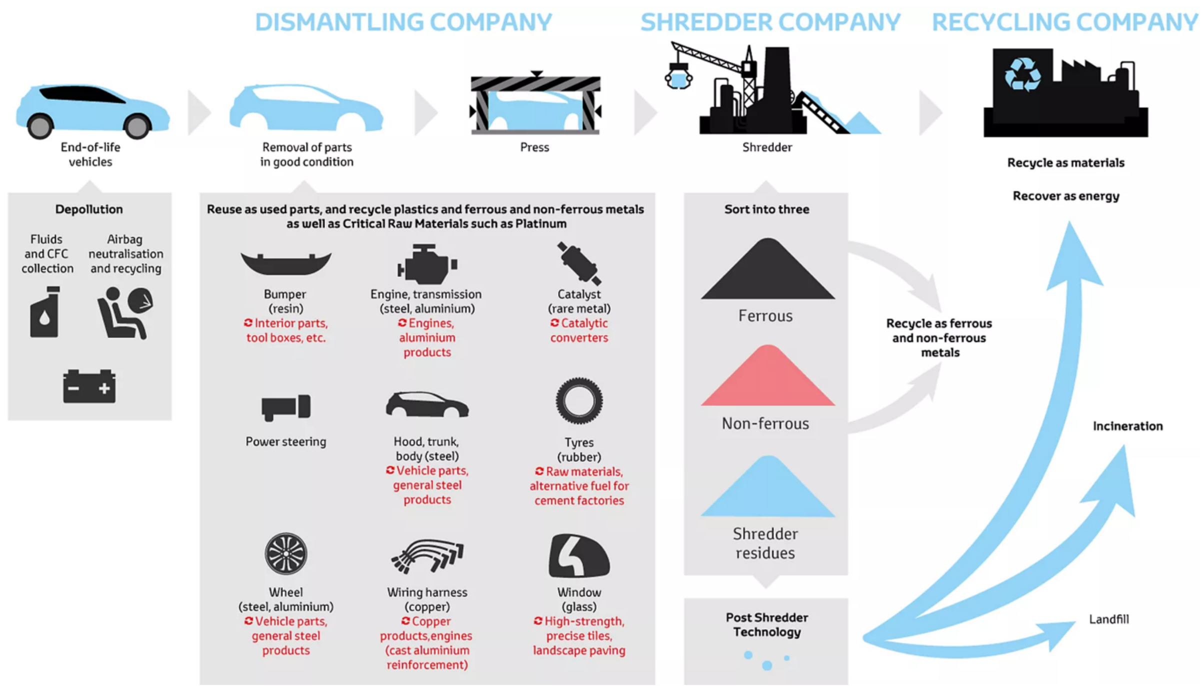

Figure 4. Visual representation of the steps for ELV management (Source: Toyota – Recycle)

4.1.2 Challenges in Achieving High Recycling Purity and Efficiency.

The directive's requirement for economic operators to achieve an 85% reuse and recycling rate of the average vehicle weight, rising to 95% when recovery processes are considered, are assessed across the entire ELV supply chain, including ATFs, shredders, and post-shredder treatment (PST) facilities. However, reaching these goals remains challenging due to material losses at various stages of the process.

ATFs play a vital role in dismantling ELVs and directly influence reuse rates by selecting components for reuse. However, the final outcome of these materials also depends on processes beyond their control. Parts and materials removed by ATFs are often assumed to be fully recycled, but factors such as contamination, technical limitations, and economic feasibility can significantly reduce actual recycling efficiency. After ATF processing, the remaining vehicle carcass goes through shredding and post-treatment, which further contributes to material losses. This chain of inefficiencies creates a gap between regulatory targets and real-world recycling outcomes.

One significant barrier to achieving high recycling purity is material contamination during shredding. For example, an Italian case study on Automotive Shredder Residue (ASR) (Cossu et Al., 2012) reveals that a substantial portion of materials sent to landfills consists of a mix of plastics, foams, textiles, and residual metals, which complicates recycling. ASR is heterogeneous, typically composed of plastics (23-41%), rubber/elastomers (9-21%), metals (6-13%), and glass (10-20%). This variation depends on multiple factors, such as the vehicle's construction year, brand, engine displacement, the technology used for dismantling, and vehicle type.

The variability in ASR composition further complicates the sorting and recovery process. Studies have shown that post-shredder technologies (PSTs) can isolate certain materials, but the mixed nature of ASR leads to contamination, particularly of valuable materials like rare earth elements (REEs) and non-ferrous metals such as copper and aluminum. When these materials are mixed with other residues, they become harder to separate, reducing their recycling potential. According to Sakai et al. (2013), detoxifying ASR is crucial for improving the purity of recovered materials and minimizing environmental risks.

A valuable option to reduce the contamination of the materials is manual dismantling. The role of manual dismantling has been explored as a way to improve material purity before shredding. A Life Cycle Assessment (LCA) study by Tasala Gradin et al. (2013) suggests that manual disassembly enhances material separation, increasing economic value and reducing contamination. In addition to improving the separation of materials like copper, manual dismantling allows for better management of the polymer fraction in vehicles.

Under shredding scenarios, the vehicle's polymers become contaminated, distorting their melting points and making recycling unfeasible. However, manual disassembly allows for the removal of these polymers in their unaltered state, making them more suitable for recycling. Polyurethane (PU), which is difficult to recycle, is typically separated for incineration. The remaining polymers can be recycled with only minor contamination, reducing the amount sent to landfills.

Similarly, glass and the "other" fraction are more effectively handled through manual disassembly. During shredding, glass often ends up in the ASR and is sent to landfills. In contrast, manual dismantling enables the recovery of windshields and other glass components for recycling.

The "other" fraction, which typically ends up in ASR and becomes contaminated during shredding, can be incinerated for energy recovery when manually dismantled, ensuring energy recovery targets are met. These findings highlight the potential of manual dismantling to overcome some key barriers to recycling and help achieve and surpass the ELV Directive's 2015 targets of 95% material recovery and only 5% landfill disposal.

However, manual dismantling faces economic challenges, such as higher labor costs and the need for skilled workers, making large-scale implementation difficult, particularly in high-wage economies. Nonetheless, studies suggest that improving material purity through manual disassembly could offset higher labor costs by increasing the overall value of recovered materials.

Another challenge lies in the limitations of existing recycling infrastructure, which is often not optimized for complex materials such as multilayered plastics, composites, and electronic components. These materials require specialized sorting and processing technologies that many ELV recycling systems currently lack. For instance, high-value components like batteries, circuit boards, and electronic sensors present recycling challenges due to their small size, hazardous content, and complex material composition.

PST facilities, while essential for recovering residual materials, face limitations in processing these complex materials. The integration of advanced separation technologies, such as sensor-based sorting or heavy media separation, has improved metal recovery, but significant barriers remain for fine fractions of ASR, such as mixed plastics and critical raw materials (CRMs).

Studies suggest that enhancing quality control in the shredding process and investing in advanced PST technologies could significantly improve recovery rates. As Sakai et al. (2013) note, introducing more sophisticated sorting systems is crucial for recovering materials like rare earth elements and non-ferrous metals, which are currently difficult to isolate due to their presence in mixed streams.

Moreover, the ASR paper highlights that the composition of ASR, with its variety of plastics, rubber, and metals, makes it challenging to achieve pure recycling streams. Although PSTs like heavy media separation and sensor-based sorting have improved metal recovery, further advancements are needed to process the fine fractions of ASR, such as mixed plastics and CRMs.

Pyrolysis and gasification, emerging as alternatives to traditional incineration, offer potential for reducing ASR volumes while recovering energy, though their application remains limited. Environmental concerns about emissions and product quality persist, particularly regarding their long-term impact. Sakai et al. (2013) emphasize the need for further research to assess the environmental impacts of these technologies, especially in terms of emissions and resource recovery efficiency.

In conclusion, addressing challenges related to purity and efficiency requires a comprehensive approach that includes both technological innovation and economic considerations. While manual dismantling, advanced sorting techniques, and thermal treatments offer pathways to improved recycling outcomes, further research and investment are necessary to overcome current limitations in processing complex materials.

Additionally, collaborative efforts across the entire ELV supply chain are essential to meet the recycling targets set by the EU while minimizing the environmental impact of these processes.

4.2. Overview of the ELV Supply Chain

The ELV supply chain is a complex system that involves multiple key actors, each playing a vital role in the dismantling, recycling, and disposal of vehicles once they have reached the end of their useful life.

In this section, an overview of the main players in the ELV supply chain is provided, outlining their roles and responsibilities. The key actors in this process are Original Equipment Manufacturers (OEMs), Authorized Treatment Facilities (ATFs), shredders, and recyclers.

4.2.1 Original Equipment Manufacturers (OEMs)

OEMs are responsible for designing and producing vehicles, and they have a significant influence on the materials and technologies used in these vehicles. This, in turn, affects the ease and efficiency of recycling and dismantling once the vehicle reaches the EoL. With the rise of stricter regulations regarding vehicle recycling, OEMs are now expected to design vehicles with not only recycling in mind but also reuse and remanufacturing.

This includes promoting concepts like "design for dismantlability" and the use of recyclable materials. OEMs also provide essential information about the vehicle, such as the types of materials used, their placement, and the overall structure. This data is invaluable for ATFs and recyclers, as it helps them carry out proper dismantling and facilitates efficient recycling.

Increasing OEM involvement in the dismantling phase, through comprehensive studies on the dismantlability of their vehicles and a continuous dialogue with ATFs, could further improve recycling outcomes.

Additionally, OEM participation in the reuse and remanufacturing markets could help optimize material recovery throughout the supply chain.

The current level of circularity among OEMs is mainly limited to recycling, waste management and recovery. A study by Montemayor and Chanda (2023) on the top 10 Fortune automotive manufacturing companies shows that the main focus is too narrow on

EVs rather than on the whole circularity of the vehicles and therefor they mainly address components related to powertrain, fuel technology and recycling.

While 50% of the analyzed companies shows level 1 initiatives on reuse, refurbish and repair, their applications are still scarce and not scalable.

4.2.2 Authorized Treatment Facilities (ATFs)

ATFs are specialized facilities that process ELVs to extract parts, materials and safely dispose of hazardous substances. They play a critical role in the first step of the recycling process by dismantling vehicles and separating parts according to material types. These facilities are licensed and regulated to ensure they meet strict environmental standards, particularly regarding the disposal of fluids, batteries, and other hazardous materials.

The dismantling process at ATFs typically involves removing valuable parts such as engines, catalytic converters, and other components that can be resold or reused. ATFs are also responsible for draining fluids, including oil, fuel, and coolant, to prevent contamination.

One of the main challenges ATFs faces is managing the balance between the cost of dismantling and the revenue generated by selling parts and materials. Dismantling a vehicle requires significant labor and time investment, yet the financial return from selling parts may not always justify these costs.

A study from Berzi et. Al (2012), following inspections done in 10 different Italian ATFs shows that the majority of the working time is spent on dismantling mechanics (about 30% of total time) and the spare parts (25% of total time) while little time is spent of depollution. An interesting fact regarding the dismantling was about wire harness which is present on the market at high price but the removal is highly time consuming, which leads the material to stay on the car.

Additionally, ATFs must evaluate the market demand and their storage capacity to ensure that, during the dismantling process, they remove parts that are in demand while leaving low-value items, type of parts that are already in storage, or those with low resale prices either on the vehicle or sent directly to recycling.

While some components can be reused, many materials do not offer sufficient value to cover the dismantling costs. Consequently, ATFs are under pressure to optimize their operations, balancing cost management and revenue generation in a way that aligns with environmental goals, without sacrificing financial sustainability.

4.2.3 Shredders

Shredders are specialized facilities or companies that use industrial machines to break down ELVs into smaller pieces for easier separation and recycling. The residual carcass, which is primarily made up of metal and non-metal components, is delivered to shredders after automobiles are disassembled at ATFs. Ferrous metals (like steel) and non-ferrous metals (like aluminum), together with other materials like plastics and glass, are separated by the shredding process. Shredding isn't always the best option, though, particularly for non-metal components that can combine and create automobile shredder residue (ASR).

Shredders are essential to the recycling process because they make it possible to treat vast amounts of ELVs rapidly and effectively. High percentages of metals can be recovered during the shredding process, but other materials, especially glass and plastics, are less successfully recovered because they can get contaminated. Recycling is made more difficult by this pollution, which frequently renders it economically unviable.

There is growing demand on the shredder sector to enhance material separation quality and lower the quantity of ASR that is dumped in landfills. Given the expanding environmental legislation and the growing market demand for increased recycling rates, this is particularly crucial. The advent of sophisticated sorting technologies, like sensor-based sorting and heavy media separation, provide viable ways to enhance material recovery and lower contamination.

4.2.4 Recyclers

The materials recovered from shredders and ATFs must be processed by recyclers. They are essential in processing and refining resources, including metals, polymers, and other materials, so that they can be used again to create new goods. Through the conversion of waste materials into useful resources, recyclers contribute to the circular economy's closure. Metals collected from ELVs, for instance, are sent to metal refineries for purification and repurposing in the creation of new automobiles or other goods.

In specialized facilities, plastics and other materials collected from ELVs are usually cleaned, sorted, and reformed into new goods. However, effective recycling may be hampered by plastic contamination during the shredding process. In order to handle the growing complexity of materials contained in ELVs, numerous recyclers are investing in and creating sophisticated sorting technology. By increasing the effectiveness and purity of material recovery, these technologies hope to increase recycling and reuse rates.

Energy recovery may occasionally involve recyclers as well. Materials that cannot be recycled can be utilized as fuel in pyrolysis or incineration, two processes that produce energy. This method offers a means of recovering energy from materials that cannot be directly reused and helps lower the amount of garbage that is dumped in landfills.

4.2.5 Interaction Between Actors

The interactions between the key actors in the ELV supply chain create a complex network, where effective communication and coordination are essential for the efficient operation of the entire system. OEMs play a critical role by ensuring that vehicles are designed for disassembly. They need to provide ATFs and recyclers with essential information about the materials and components used in their vehicles. Additionally, OEMs should increase the reuse of parts in their activities to optimize the recycling process.

ATFs, in turn, are responsible for properly dismantling vehicles to maximize the recovery of valuable parts. They need to work closely with shredders and recyclers to ensure that the materials recovered from dismantling are of high quality and can be reused effectively. Shredders and recyclers must collaborate to ensure that non-metal components, such as plastics and glass, are properly sorted and processed to meet the stringent recycling standards set by regulatory bodies.

All actors in the supply chain rely on each other to meet the recovery and recycling targets established by the EU and other regulatory authorities. However, the ELV supply chain faces several challenges, such as the increasing complexity of vehicle materials, stricter environmental regulations, economic inefficiencies, and the need for advanced technologies to handle mixed materials like ASR.

Addressing these challenges will require enhanced collaboration across the entire supply chain. In addition, continuous innovation and investment in new recycling technologies will be crucial to improving material recovery rates and ensuring the long-term sustainability of the ELV recycling process.

4.3. Case Studies: ELVs Management in Europe

In 2022, the European Union reported a total of 4,668,000 ELVs, with Italy, Spain, and France accounting for 56% of this figure, specifically 2,602,481 vehicles. These countries represent significant portions of the overall ELVs in the market, making them key players in the region's ELV recycling and recovery landscape.

Given their contribution to the ELV volume, they offer important insights into the current state of the market, recycling practices, and recovery rates. This chapter will explore the ELV recycling systems in Italy, Spain, and France, with a focus on their varying approaches, regulatory frameworks, and the challenges they face in ELV management.

4.3.1 Italy

The European Directive was transposed in Italy through Legislative Decree No. 209 of 24 June 2003, titled 'Implementation of Directive 2000/53/EC on End-of-Life Vehicles. Similarly to the Directive's approach, the Italian legislative decree presents a lack of clear targets and timeline to ensure that ELVs are not only correctly disposed of but that they're also recycled and reused as much as possible.

The Decree doesn't show a clear path to ensure that communication and collaboration among all parties is ensured, therefor reiterating just the overall path followed by the European Commission.

One of the main issues is the lack of integrated governance among key stakeholders, including vehicle manufacturers, dealerships, insurance companies, and treatment operators. Instead of fostering coordinated efforts, the Italian legislation has largely delegated the responsibility for collaboration to voluntary agreements among these actors. As a result, the intended synergies and integrated management practices have not materialized, leading to inefficiencies and fragmented implementation.

Furthermore, the model established by Legislative Decree No. 209/2003 is predominantly structured around pre-existing market dynamics, with minimal intervention to encourage more sustainable practices. While the decree sets recycling and recovery targets, it does not impose specific measures to innovate or reshape the operational practices of stakeholders. Consequently, despite the formal imposition of targets, there has been limited progress in adopting more efficient management models.

The decree also emphasizes the development of post-shredding separation technologies to reduce the production of automotive shredder residue (ASR). However, despite technological advancements and experimental practices aimed at optimizing ELV dismantling and processing, the lack of direct incentives and targeted support has limited the practical application of these innovations.

Lastly, Italy has struggled to consistently meet the overall recovery targets established by the European Directive. This underperformance highlights structural deficiencies within the current regulatory framework, which fails to adequately address the practical challenges of ELV management. Therefore, a comprehensive reform of the legislation is necessary to remove existing barriers and promote more effective practices, ensuring alignment with EU expectations and sustainability goals.

Following the implementation of the Italian legislation on End-of-Life Vehicles (ELVs), a significant step towards improving the management and recovery of ELVs was the signing of a Program Agreement in 2008. This agreement was aimed at enhancing collaboration between various stakeholders, including the Ministry of the Environment, the Ministry of Economic Development, and industry associations such as ANFIA, UNRAE, and ASSODEM. The agreement outlined key objectives, including the development of pilot projects to improve collection centers and technology for post-fragmentation, as well as the promotion of environmentally sustainable practices within the sector.

Despite significant progress in the management of end-of-life vehicles (ELVs) in Italy, there remain substantial challenges that hinder the effective implementation of circular economy principles. According to the study *"Veicoli fuori uso: nodi e potenzialità verso l'economia circolare"* by Stefano Leoni, these challenges include a weak governance model, insufficient coordination between key stakeholders (producers and treatment operators), and a lack of clear roles in the treatment process. The study highlights that market volatility, inadequate infrastructure, and insufficient targets for recycling and reuse further complicate the situation. Moreover, there is a pressing need for better tracking of treatment performance across different car brands, as well as improved information on hazardous materials in ELVs.

Leoni proposes several solutions, including the introduction of an Extended Producer Responsibility (EPR) regime to enhance accountability and incentivize the use of recycled materials in new vehicles. The proposal also stresses the importance of setting specific recycling targets for individual materials, providing rewards for cars with higher recycled content, and investing in research to develop new recycling techniques. These suggestions aim to address current gaps and promote a more sustainable and circular approach to vehicle end-of-life management in Italy.

In line with these observations, the 2022 ISPRA report provides valuable data reflecting the ongoing challenges faced by Italy's ELV recycling sector. According to the report, the percentage of reuse and recycling reached 86% in 2022, surpassing the 85% target set by Italian law (Decree No. 209/2003). However, this performance represents a decline compared to 2021 figures. Several factors contributed to this, including a drop in car registrations, supply chain disruptions, and delays in vehicle production. Although total recovery, including energy recovery, should reach 95% according to European legislation, Italy's recovery rate remains at 86%, primarily due to the negligible energy recovery in the country.

One of the primary challenges remains the disposal of automotive shredder residue (ASR) or "fluff," which is mostly directed to landfill, over 162,000 tons in 2022. While the fluff has a high calorific value and could be utilized for energy recovery, its disposal continues to be a major issue due to the lack of suitable treatment facilities and effective decontamination processes.

This ongoing problem underscores the importance of improving infrastructure and developing better treatment options, as well as incorporating energy recovery techniques, which are widely adopted in other EU member states.

Additionally, the proposed ELV Regulation will impose a non-landfill obligation regarding ASR which will pose critical complications to the current Italian situation.

A study presented at the 2024 ADA event regarding the future for ATFs in Italy, shows the results of a trial held by RMB, one of the leading multifunctional platforms for the recovery of special, hazardous, and non-hazardous waste. Considering 705 vehicles, equals to 786,500 kg of material, 500,740 kg were remaining as car bales and sent to the recovery plant.

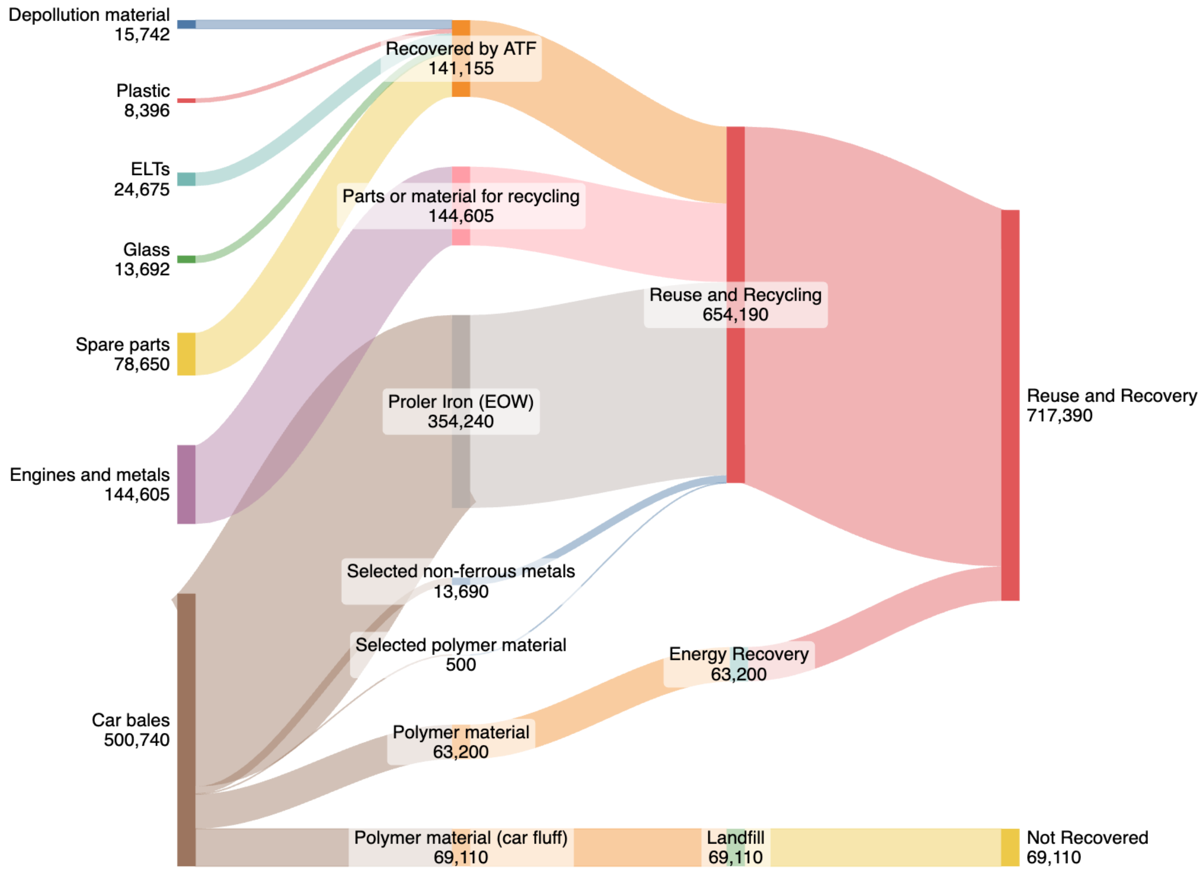

Figure 5. Visual representation of the study held by RMB
(Source: personal elaboration of the data reported by RMB in 2024)

The study reported an overall 83,18% for reuse and recycling, reuse and recovery at 91,22% which is given by adding the polymer material that is sent to energy recovery. The remaining 8,79% was sent to landfill and therefor the 95% target was not achieved.

The increase of the portion of recovered material will be mandatory to be increased in the future to comply with art. 35 of the proposed ELV Regulation regarding the “Ban on landfilling of non-inert waste”.

Therefore, Italy will need to address the current issues surroundings the energy recovery system. For Utilitalia, while the concept of energy recovery from waste has gained attention, there is a notable gap in infrastructure for effective waste-to-energy solutions which cause much of the country's waste still being disposed of in landfills.

From the 2002 analysis of Anpa regarding the ASR, the problematics regarding the correct recovery of its materials are still present now. As reported at that time, the most common disposal method for the non-metallic residue from vehicle shredding was landfill as it is now. The alternative disposal methods, which are not yet applied in Italy due to a lack of appropriate facilities, include thermal treatment (incineration or pyrolysis) and combustion in cement or steel industries.

Examining the distribution of facilities across the country, it becomes clear that the North hosts a significant proportion of these plants, particularly in the scrapping category, where the number of facilities is more than six times higher than in the South. The only category that shows a comparable distribution is vehicle dismantling plants (ATFs), which align with the reported number of vehicles treated.

Plant Type	North	Center	South	Italy
Material recovery plants	2.593	788	1.281	4.662
Vehicle dismantling plants	616	229	603	1.448
Scrapping plants	59	26	9	94
Crushing plants	15	6	7	28
Production plants that carry out material recovery	774	224	230	1.228
Chemical-physical biological treatment plants	403	204	208	815
Storage plants	948	340	425	1.713
Co-incineration plants	193	58	45	296
Incineration plants	43	7	20	70
Landfill plants	146	43	72	261
Composting and anaerobic digestion plants	115	27	49	191
Total	**5.905**	**1.952**	**2.949**	**10.806**

Table 4. Facilities present in Italy for waste management
(Source: Inspra, Rapporto Rifiuti Speciali, 2024)

The unequal distribution of ELV treatment facilities between the North and South of Italy could create several challenges for the supply chain. The North, with a higher concentration of facilities, might face logistical issues such as longer transit times and increased costs for transporting vehicles from the South.

Additionally, this imbalance could lead to processing delays, bottlenecks, and varying treatment standards across regions, potentially affecting the efficiency of recycling and recovery processes. To address these challenges, investment in infrastructure in the South or a more balanced distribution of facilities may be necessary to ensure smooth operations and compliance with environmental standards.

If we look at the number of ATFs and the related number of treated vehicles in tonnes per year, the situation do not match the distribution showed regarding the plants.

	2020		2021		2022	
	ATFs [n]	ELVs [t/y]	ATFs [n]	ELVs [t/y]	ATFs [n]	ELVs [t/y]
North	626	575.791	613	638.254	616	432.391
Center	212	215.242	217	253.090	229	181.639
South	579	426.482	600	512.810	603	399.909
ITALY	**1.417**	**1.217.515**	**1.430**	**1.404.154**	**1.448**	**1.013.939**

Table 5. Number of ATFs and treated vehicles in the last reported 3 years
(Source: Inspra, Rapporto Rifiuti Speciali, 2024)

While the North remains the area with most ATFs centers and treated vehicles, it's followed closely by the South. While qualitative reports are not available, it can be assumed that similar values for reuse, recycling and recovery are reported by both areas. While now incinerators are not used to recover the ASR, it is important to highlight that the lack of plants and unbalanced distribution further impact the current efficiency of the supply chain.

As for shredders, which are currently at the end of the supply chain, they are not widely distributed across the territory but appear to be concentrated in certain areas near industrial scrap recovery plants and in regions where the industrial fabric is more structured. Moreover, almost all of the material recovered in these plants is, in fact, metal scrap intended for steel mills.

If we consider that Italy maintains the same level of reuse and recycling also for reuse and recovery, which is 86%, it means that the remaining share is left to landfill which is equal to 141.951,46 tonnes of waste. As reported by Ispra, ASR is characterized by an average calorific value of 13.000-15.000 kJ/kg, therefore, it can be used as a fuel alternative to traditional fuels.

While incineration is not the best solution, especially when considering the high potential for reuse and recycling of the parts and materials present in ELVs, it still offers a better alternative than landfill, where the overall value of the material is completely lost. Additionally, in light of the proposed ELV Regulation, the overall management system needs to adopt WTE (Waste-to-Energy) solutions to ensure that the 95% reuse and recovery target will be met in the future.

The main issues encountered involve not only the costs of processing such products, which make landfilling a cheaper solution for the system, but also the capability of the plants available in the country. In Italy, the limited number of incineration plants that can process car fluff, combined with technical challenges, local resistance, and uncompetitive prices, has made it difficult to fully harness its energy recovery potential.

Moreover, improper dismantling practices in the recycling chain can result in contamination, further complicating the efficient recovery and recycling of materials. Addressing these issues requires both investment in plant capabilities and better oversight of the dismantling and treatment processes to improve recycling rates and reduce the reliance on landfilling.

4.3.2 France

In France, the ELV Directive was initially transposed into national legislation through *Décret n°2003-727 du 1 août 2003*, which addressed vehicle construction and ELV management. This decree was later abrogated by *Décret n°2007-1467 du 12 octobre 2007*, which integrated the provisions into the *Code de l'environnement*.

Currently, the ELV Directive has been transposed into national legislation primarily through the *Code de l'environnement, particularly under Livre V, Titre IV (Déchets), Chapitre III, Section 9: Voitures particulières, camionnettes, véhicules à moteur à deux ou trois roues et quadricycles à moteur* (Articles R543-153 to R543-168).

These provisions establish the framework for Extended Producer Responsibility (EPR) and outline the roles and obligations of dismantling centers, producers, and economic operators involved in ELV management.

While the Italian legislation remained almost the same since the original legislation, France had a more proactive spirit towards the laws regarding ELVs. After inserting various articles in the Code, additional decrees were emanated in recent years regarding specific articles and by adding additional targets to increase the overall efficiency and collaboration between the numerous actors in the supply chain.

While articles regarding parts and materials removed from vehicles as well as the overall state of the ATFs is in line with the ELV Directive and the Italian legislature, additional requests are added regarding the non-metallic shredding residues which cannot be disposed of if post-shredding sorting was not used. Additionally, the French legislation also asks ATFs to mark parts' origins and destinations to ensure traceability which also facilitate the reuse of the parts when needed.

Furthermore, since January 1, 2024, ELV centers are required to have a contract with an eco-organization or, where applicable, with an individual system set up by vehicle producers in order to improve the monitoring and processing of ELVs. Eco-organizations become then the intermediary between ATFs and OEMs that handle the management of ELVs on behalf of the OEM and ensure that the target set by the government are met.

The decree of 20 November 2023 containing the specifications for eco-organizations, individual systems and coordinating bodies for the ERP sector for passenger cars, vans, two- or three-wheeled motor vehicles and motor quadricycles, completed the construction of the regulatory framework by adding intermediate targets regarding various stages of the ELV management, as shown below:

<table>
<tr><th>Vehicle Category</th><th>Target Type</th><th>2024</th><th>2025</th><th>2026</th><th>2028</th></tr>
<tr><td rowspan="7">Passenger Cars / Light Commercial Veh.</td><td>Collection[1]</td><td colspan="2">65%</td><td>68%</td><td>70%</td></tr>
<tr><td>Reuse/Recycling</td><td colspan="4">85%</td></tr>
<tr><td>Reuse/Recovery</td><td colspan="4">95%</td></tr>
<tr><td>Parts Reuse[2]</td><td colspan="2">8.5%</td><td>10%</td><td>16%</td></tr>
<tr><td>Air conditioning gas recovery</td><td>-</td><td colspan="2">60 gr</td><td>100 gr</td></tr>
<tr><td>Glass</td><td>-</td><td>-</td><td>50%</td><td>65%</td></tr>
<tr><td>Plastic (PP and PE)</td><td>-</td><td>-</td><td>65%</td><td>70%</td></tr>
<tr><td rowspan="3">Two/Three-Wheeled Motor Vehicles</td><td>Reuse/Recycling</td><td colspan="4">85%</td></tr>
<tr><td>Reuse/Recovery</td><td colspan="4">95%</td></tr>
<tr><td>Parts Reuse</td><td colspan="2">26%</td><td>31%</td><td>40%</td></tr>
<tr><td rowspan="3">Light Quadricycles</td><td>Reuse/Recycling</td><td colspan="2">66%</td><td>69%</td><td>73%</td></tr>
<tr><td>Reuse/Recovery</td><td colspan="2">87%</td><td>92%</td><td>95%</td></tr>
<tr><td>Parts Reuse</td><td colspan="2">3%</td><td>4%</td><td>6%</td></tr>
</table>

Table 6. Different targets regarding the various vehicle categories
(Source: personal summary from the targets reported in the Decree of 20 November 2023)

The various targets set by the decree in cooperation also with Ademe, the French Agency for Ecological Transition, demonstrates a proactive commitment in ensuring the correct management of ELVs. By focusing on specific materials and components, and by setting

[1] Collection targets are calculated as the ratio of the total number of End-of-Life Vehicles (ELVs) taken in charge by authorized centers over the past three years to the total number of new vehicles placed on the national market during the same three-year period.

[2] Part reuse is defined as the percentage of the mass of vehicle parts, resulting from ELV dismantling, that have been prepared for reuse, relative to the total mass of ELVs processed. Batteries and tires are excluded from this calculation.

targets for parts reuse, hazardous substances and valuable resources, they can be more effectively managed.

While potentially increasing the administrative burden and costs, the decree mentions the possibility to adapt the targets in case, following analysis conducted with Ademe, a modification is needed.

The situation in France regarding ELVs and its management has been reported over the years by Ademe. In the last report of 2024, regarding the year 2022, 1,759 approved ELV centers were recorded, an increase of 23 units compared to 2021. Similarly, the number of approved shredders rose to 61, up from 60 in the previous year.

In 2022, a total of 1,877,811 vehicles of all types were placed on the market, representing a decrease of 10.2% compared to 2021. Notably, nearly one in two vehicles (43%) was either a hybrid or electric model, marking a significant increase from the 36% recorded in 2021.

In 2022, a total of 1,168,225 ELVs were reported as processed by approved ELV centers, amounting to 1,346,729 tonnes. This represents a decrease of 13.2% and 11.8% respectively compared to 2021. The average mass of ELVs reached 1,152.8 kg, marking an increase of 1.6% from the previous year.

Table 7 summarizes key data on the recycling and recovery performance of ELVs in 2022, highlighting the percentages of materials extracted, recycled, and reused, as well as the overall efficiency of French ELV centers and shredders:

Category	Weight [kg/ELV]
Waste extracted before shredding	277.1
Materials (excluding waste and tires) destined for recycling or recovery	123.5
of which: metals	110.1
Materials (excluding batteries and tires) destined for reuse	101.29
of which: metals	70.1
Materials recycled by shredders	610.6
Materials recovered for energy recovery	56

Table 7. Summary regarding recycling and recovery performance of ELVs in 2022
(Source: personal summary for the 2024 report by Ademe)

Once ELVs are collected, mainly from private individuals as shown in Figure 6, they are delivered to ATFs, where the treatment process begins. Just like Italy, depollution is the first mandatory step in the process where components such as batteries, used oils, coolant, and air conditioning fluids are removed.

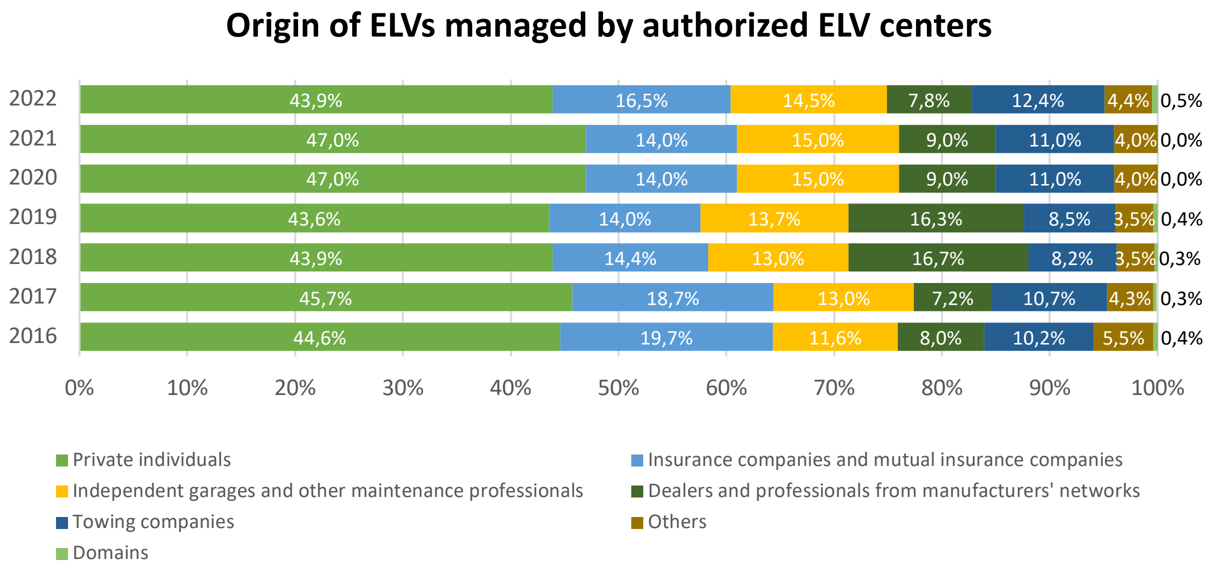

Figure 6. Graph reporting the different origins of ELVs (Source: 2024 report by Ademe)

In 2022, 34,342 tonnes of depollution waste were generated, equivalent to 29.4 kg per ELV. Among these wastes, 80% were recycled, 9% underwent energy recovery, and 11% were reused, mainly in the form of batteries.

Regarding tyres, which is the next mandatory step reported by Ademe, in 2022, a total of 45,789 tonnes of tyres were dismantled, representing 39.2 kg per ELV processed. Of these, 33.3% were reused, 29% were recycled, and 31.1% were sent for energy recovery, while the remaining 4.6% were reused by collectors.

In 2022, a total of 144,304 tonnes of materials were extracted from ELVs for recycling or recovery (excluding tires), which is approximately 123.52 kg per ELV processed. Nearly 100% of these materials were destined for recycling by weight. As in previous years, the majority of materials sent for recovery in 2022 were ferrous metals, accounting for 76.1% of the materials dismantled for recovery.

The tonnage of materials extracted from ELVs increased by 13.4% compared to 2021. When considered per vehicle, the average mass extracted for recovery increased from 108.9 kg in 2021 to 123.53 kg in 2022. This overall increase in the average mass extracted per vehicle was mainly due to metals, with the average mass of metals dismantled per vehicle rising from 95.4 kg in 2021 to 110 kg in 2022. The extraction of non-metallic materials for recovery remained stable, at 13.47 kg per vehicle in 2022, compared to 13.49 kg per vehicle in 2021. Bumpers and fuel tanks were the primary non-metallic materials extracted for recycling, while the extraction of other plastics remained minimal.

The average quantities reported in kg/ELV for 2022 are shown Table 8 below:

Material dismantled for recovery	Quantity recycled	Quantity used for energy recovery	Total	Total [%]
Ferrous metals	94,05	0	94,05	76,14%
Non-ferrous metals	16,00	0	16,00	12,95%
Other rubbers	0,03	0	0,03	0,02%
Catalytic converters	4,61	0	4,61	3,73%
Wiring harnesses	1,03	0	1,03	0,83%

Paint	0,00	0	0,00	0,00%
Polyurethane foams	0,05	0	0,05	0,04%
Polypropylene (PP) bumpers	3,42	0,04	3,46	2,80%
Polypropylene (PP) other parts	0,29	0	0,29	0,23%
Polyethylene (PE) fuel tanks	1,25	0,02	1,27	1,03%
Polyethylene (PE) other parts	0,03	0	0,03	0,02%
Polyamides (PA)	0,01	0	0,01	0,01%
ABS, PVC, PC, PMMA, PS, etc.	0,04	0	0,04	0,03%
Textiles, others	0,04	0	0,04	0,03%
Glass	2,62	0	2,62	2,12%
Total	**123,47**	**0,06**	**123,53**	**100%**

Table 8. Average quantities of material per ELV
(Source: 2024 report by Ademe)

Regarding reuse, in 2022, 99,937 tonnes of parts were dismantled for reuse (excluding tires and batteries), which amounts to an average of 85.5 kg per ELV processed. 360 ATFs, whose declarations were verified and certified, did not dismantle parts for reuse, accounting for 30% of ATFs, compared to 32% in 2021 for a similar number of certified declarations. The majority of ATFs, therefore, dismantle parts from the ELVs they process.

Once the vehicle has been treated by the ATF it reaches the shredder site. In 2022, a total of 1,181,138 carcasses were sent to shredders, amounting to 1,023,270 tonnes, marking a decrease of 18% in units and 24% in tonnage compared to 2021. The average weight of carcasses remained stable at 866.3 kg (865,8 kg in 2021). The reduction in the number of ELVs collected and dismantled by ATFs led to a corresponding decline in the number of carcasses sent to shredders.

On average, 277.66 kg of materials were removed from each ELV before shredding, slightly increasing from 261.85 kg in 2021, mainly due to the rise in the amount of material extracted for recycling. Notably, ATFs supplied fewer carcasses to shredders than the number of ELVs they processed (a gap of -24%). This difference may arise due to time lags (e.g., sending recorded in one year and receiving in the next) or different measurement tools.

In 2022, fluff remained the largest material generated during shredding, with a slight decline in recycling (-2%) and an increase in energy recovery (+2.2%). The amount of fluff sent to landfills remained stable compared to 2021 (25.2% in 2022 vs. 25.3% in 2021), with its recycling rate decreasing (34.8% in 2022 vs. 36.8% in 2021).

The overall recovery of non-metallic materials from shredded ELVs was 77.4%, a small improvement from 2021. The share of recycled materials rose to 42.6%, while energy recovery dropped slightly to 34.8%.

The various flows of materials recovered by ATFs and then separated at shredding site and summarized in Figure 7:

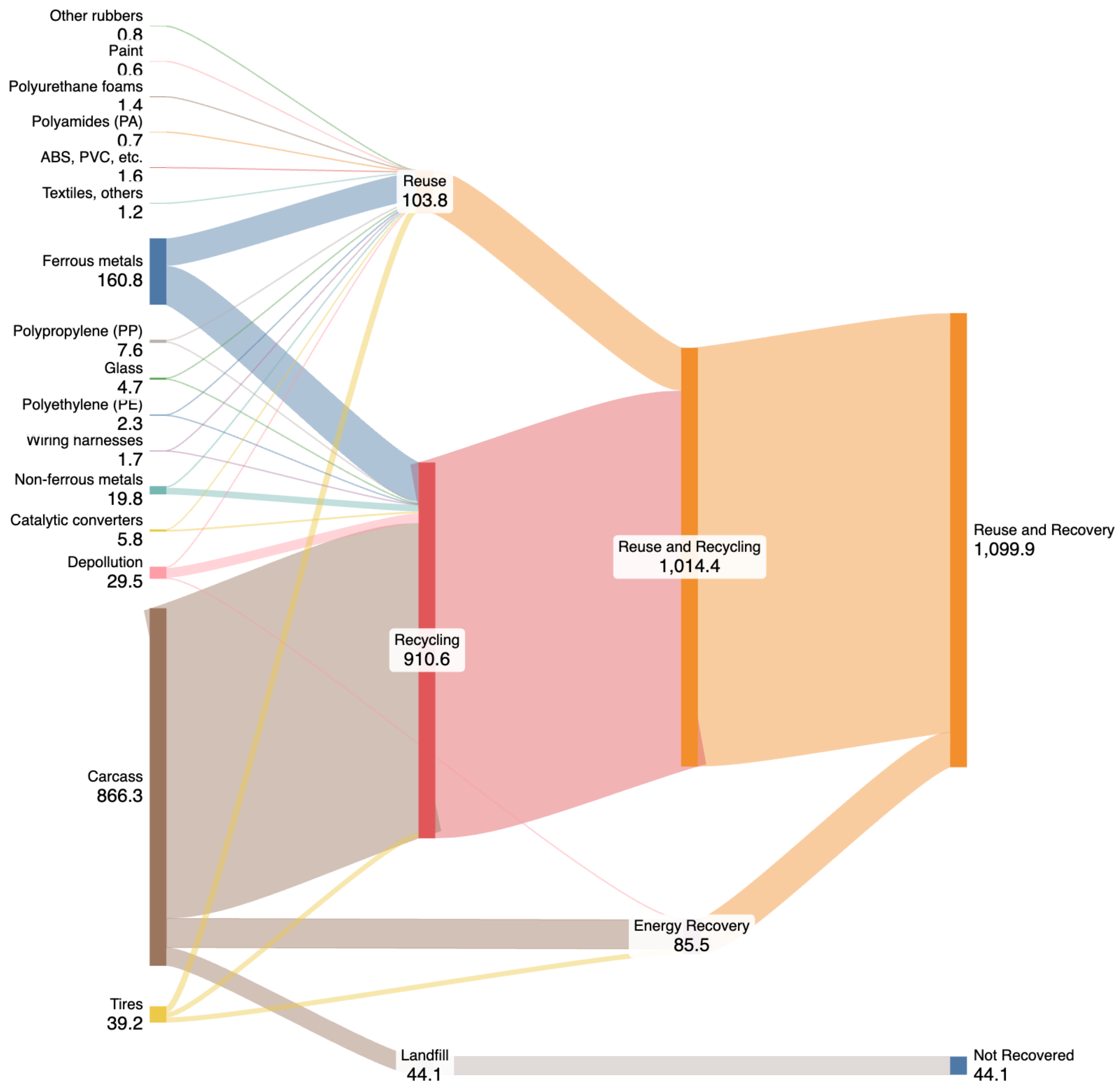

Figure 7. Visual representation of the reported quantities of 3Rs by Ademe
(Source: personal representation of data from 2024 report by Ademe)

By considering the average weight of an ELV equals to 1144 kg/ELV, as reported by Ademe for 2022:

- 1014.4 kg goes in reuse and recycling, making up 88,67% of the overall weight
- By adding 85.5 kg in energy recovery, 1099.9 kg goes in reuse and recovery, making up 96,15% of the overall weight
- The remaining 44.1 kg, equals to 3.85% of the weight, which is mainly composed of glass (19%), polypropylene (17,7%) and polyurethane foams (14,1 %), was sent to landfill and therefore remained unrecovered

The targets for reuse, recycling, and recovery have been consistently met and surpassed, demonstrating that the current supply chain is effectively adhering to the goals set by the Directive. Since 2013, the reuse and recycling rate has reached 85.3%, while the reuse and recovery rate first met the target in 2019, achieving 95%.

Although the supply chain appears to function efficiently, some concerns arise regarding the accuracy of the data. This is due to the outdated vehicle composition data and discrepancies between figures reported by different stakeholders, which could potentially impact the reported rates.

Nevertheless, both Ademe and SYDEREP have been instrumental in collecting and analyzing data not only in aggregate terms but also by providing detailed quantities of materials per ELV and their treatment. This includes examining the current operations of shredders to separate various materials in the vehicle carcass. Such attention to detailed reporting, along with proactive regulatory measures, has strengthened ELV management. These efforts have also ensured the supply chain is well-prepared for the recent ELV Regulation.

The role of the networks established among various actors, including manufacturers, shredders, and treatment centers, has also been crucial in fostering collaboration and improving overall performance, supporting a more efficient and cohesive ELV management system.

4.3.3 Spain

In Spain, the ELV Directive was initially transposed into national legislation through *Real Decreto 1383/2002, de 20 de diciembre*, which established regulations for the management of end-of-life vehicles. This decree was later replaced by *Real Decreto 265/2021, de 13 de abril*, which updated and consolidated ELV-related provisions, incorporating modifications introduced by the *Real Decreto 20/2017*.

Much like Italy and France, the Spanish Decrees follow the overall path set by the Directive by reporting the target for reuse and recycling and reuse and recovery, the technical requirements for ATFs, the parts and materials that need to be removed to facilitate the recycling as well as the obligations for OEMs under the EPR system which can be fulfilled either individually or through collective systems with other economic agents.

Additionally, from the *Real Decreto 20/2017*, Spain introduced specific targets for the marketing and reuse of vehicle parts and components. Starting February 1, 2017, ATFs were required to recover and market parts and components representing at least 5% of the total weight of the vehicles they processed annually for preparation for reuse.

This target increased to 10% in 2021 and is set to reach 15% by January 1, 2026. These objectives must be met in each autonomous community, proportional to the number of vehicles permanently deregistered within that region in the corresponding year.

The data regarding the management of ELVs in Spain is redacted by the Ministry for the Ecological Transition and the Demographic Challenge (MITECO). The last available report was published in 2023, with data regarding 2020 and 2019.

The reported number of ATFs in the country was 1.236. The number of vehicles treated was 713.404, a decrease of 12,33% from 813.768 from 2019, with an overall weight of 949.916 t. As the first year of the pandemic, the drop in processed ELVs aligns with the situation for the automotive market at the time.

Passenger cars' registrations dropped from 1.375.381 in 2019 to 939.096 in 2020, a drop of 31,72%. De-registrations dropped by 11,60%, from 879.446 to 777.465.

In terms of materials recovered at ATFs site and later at shredding site, the waste flows are shown in the diagram below:

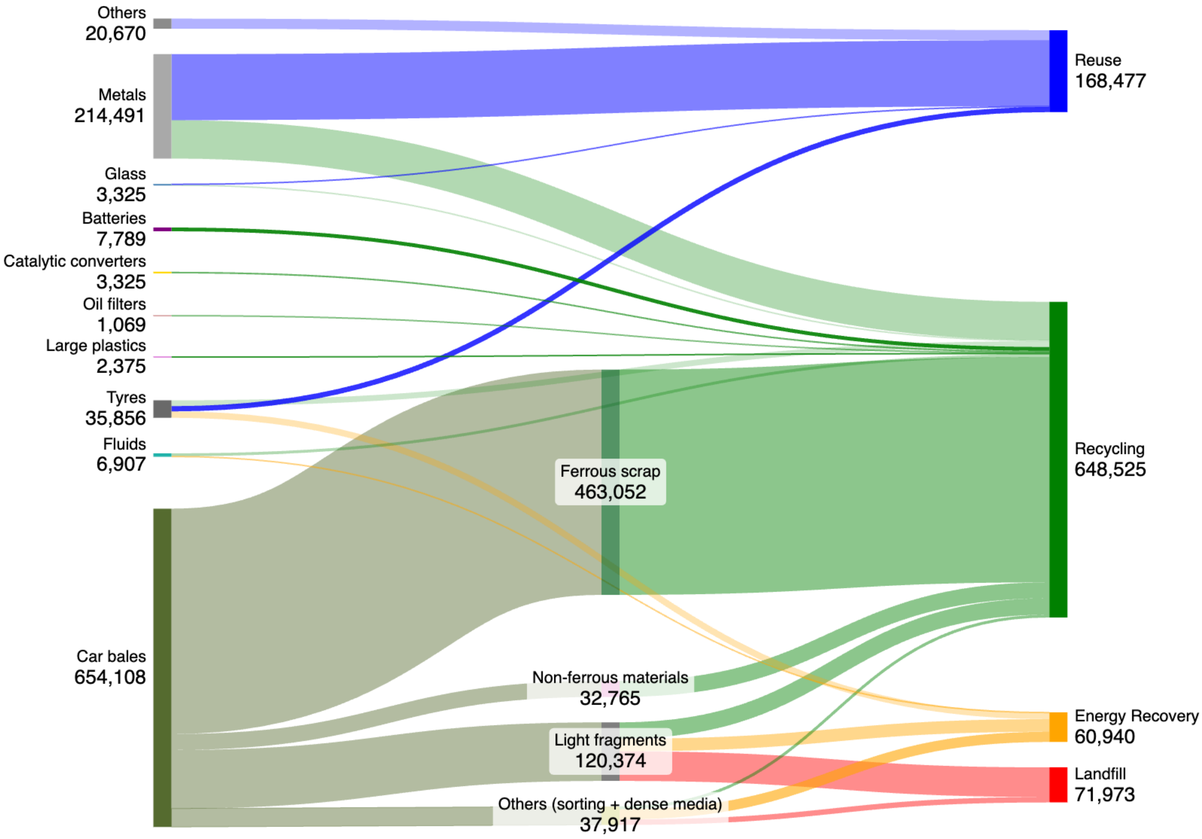

Figure 8. Visual representation of the reported quantities of 3Rs by Ademe (Source: personal prepresentation of data reported by MITECO in 2023)

Overall, in 2019 Spain reported:

- 168.477 t for reuse and 648.525 for recycling, amounting to 817.002 out of 949.915 t of waste resulting in 86% for reuse and recycling
- 60.940 t for energy recovery that summed with reuse and recycling results in 877.942 t, equals to 92,4% which is below the 95% target set by the ELV Directive
- The remaining 71.973 t were sent to landfill, equals to 7,58%

By analyzing the materials reported for ATFs and shredders from 2010 to 2019, showed respectively in Figure 9 and 10, the highest share of reuse and recycling is given by metals in all the reported years.

When considering the material coming from ATFs, the share of reuse for metals has increased from 9,87% in 2010 to 14,28% in 2019 highlighting an important increase for the preferred route in terms of recovery for materials. At the same time, also metals sent to recycling increased from 6,20% to 8,30% out of the overall yearly reported waste.

Overall, the total share of reuse by ATFs increased from 26,56% in 2010 to 32,41% in 2019 while recycling increased from 10,70% to 11,92% in the same period. Energy recovery remained steady throughout the years and it's mainly composed of tyres, the preferred solution for this type of components.

When considering the material coming from shredders, the report aggregated the material into ferrous material, non-ferrous material, light fragments and others. What reaches the shredders is the remaining of the vehicles after being treated by ATFs and therefor it corresponds to the majority of the treated materials.

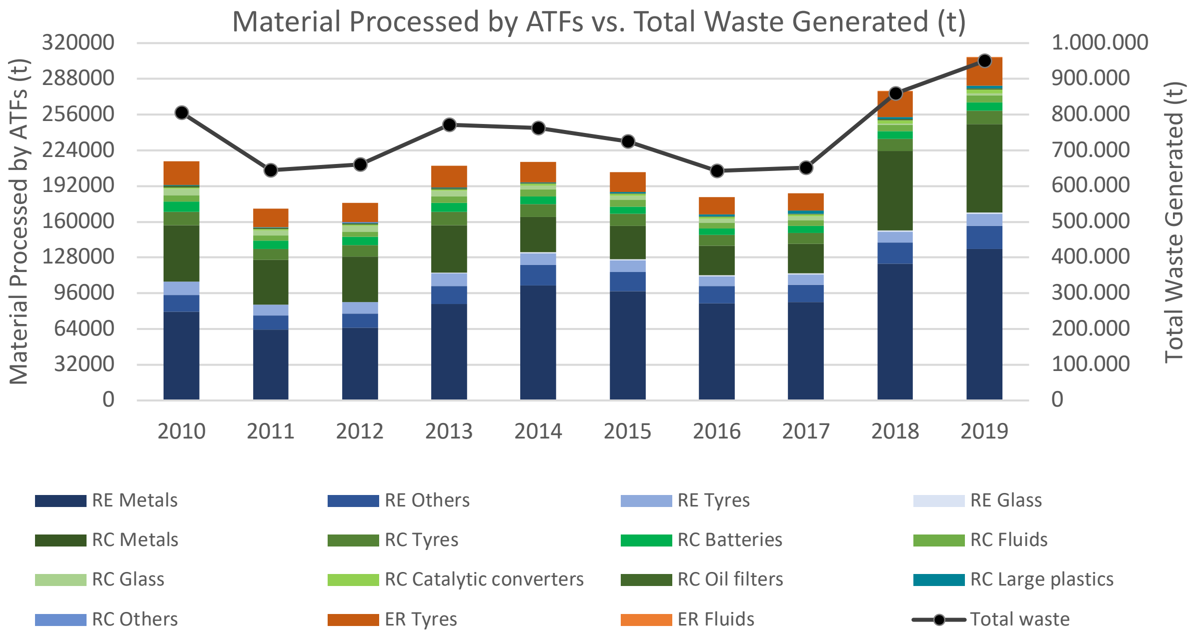

Figure 10. Material processed by ATFs compared to the total waste generated (Source: personal representation of data reported by MITECO in 2023)

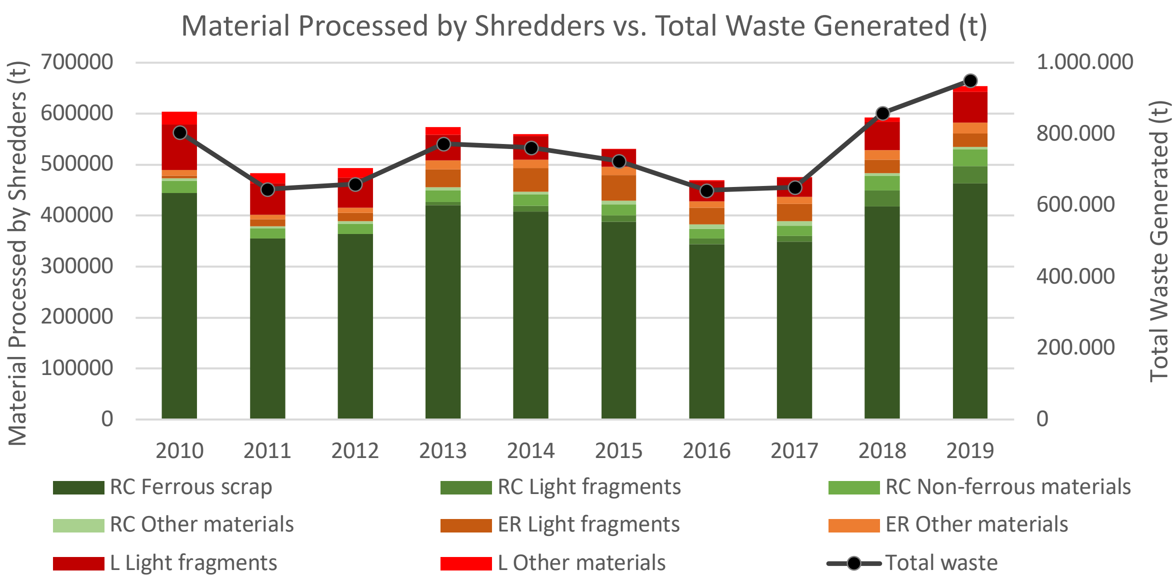

Figure 9. Material processed by shredders compared to total waste generated (Source: personal representation of data reported by MITECO in 2023)

In 2010 74,99% of the material was treated by shredders and this share slowly decreased reaching 68,86% in 2019, delineating that a higher share of materials is being removed by ATFs themselves.

Most of the material treated by shredders reaches recycling, with ferrous scrap being the largest component. The overall share reported in 2010 was 58,82% which decreased and reached 56,35% in 2019. This was impacted also by the increase in the reuse of metals by

ATFs. The share of energy recovery instead increased from 2010 to 2019, mainly due to the increased energy recovery of light fragments such as residue of plastics, foam and textiles.

The share of landfill decreased from 14,26% in 2010 to 7,58% in 2019, highlighting an overall improvement for the recovery of materials. This was mainly cause by the increased recycling and energy recovery of the light fragments.

The report also focuses on the so-called 'Coordinated Network of Treatment Facilities' (Red Concertada de Instalaciones de Tratamiento), a network of authorized centers specifically designated to manage the treatment of ELVs in compliance with environmental regulations.

Founded in 2003, this network is coordinated by SIGRAUTO, a non-profit association dedicated to providing solutions for environmental obligations and ensuring the proper disposal and treatment of ELVs. The latest SIGRAUTO report is used to further clarify the current state of the supply chain, proposing that the conditions reported by network members could also be applicable to the rest of the country.

Additionally, SIGRAUTO manages the network of treatment facilities that vehicle manufacturers use to comply with ELV regulations in Spain. It provides support services, helps resolve administrative and treatment-related issues, and ensures that facilities receive industry updates to stay informed about sector developments.

Below a summarizing table regarding the evolution of the network is presented:

Members	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
ATFs	504	518	528	528	523	569	577	569	579	587	597
Shredders	31	29	28	26	26	26	26	25	24	24	25
Post-shredders	10	10	10	10	10	10	10	10	9	9	9

Table 9. Evolution of SIGRAUTO network from 2014 to 2024
(Source: SIGRAUTO annual report 2024)

ATFs part of this network has been steadily increasing since 2014, except for 2018 and 2021 where the network decreased by some units. Both shredders and post-shredders number have decreased from 2014.

SIGRAUTO reported that the number of vehicles processed by ATFs in Spain dropped by 5.92% in 2023 compared to 2022, reaching 601,607 units, the lowest reported level of Spain in this century. This decrease is attributed to factors like the lack of vehicle fleet renewal, influenced by the rising cost of living, uncertainty about new vehicle technologies, and the absence of effective institutional support for vehicle renewal plans.

As a result, ELVs are reportedly getting older every year: in 2014 the average age was 16,48 years which increased to 21,08 years in 2023. While this can be a positive signal regarding the long lifespan of such products it also may cause additional danger for the operators that treat such old vehicles.

Additionally, SIGRAUTO also reported that the purging of outdated vehicle registrations by the General Directorate of Traffic and the ineffectiveness of current vehicle renewal plans have impacted the average age of ELVs. Despite these challenges, motorcycle and heavy industrial vehicle treatment numbers have increased, with growth rates of 12.37% and 8.11%, respectively.

The overall situation delineated by MITECO and SIGRAUTO, in their respective reports, shows an ELVs management system that is currently struggling to reach the target present in the Directive for reuse and recovery and at the same time, has still not recovered from the pandemic due also to the current crisis of the automotive sector and the decrease in purchasing power of consumers.

Therefore, the current capacity of the country in terms of ATFs exceeds the current demand for dismantling, which could in turn heavily impact the economic sustainability of these plants. Additionally, the proposed new list in the Regulation of parts and components that will need to be removed by ATFs during dismantling, further increases the operational burden.

As an active participant in the discussion related to the proposed ELV Regulation, SIGRAUTO has in fact opposed the new list of mandatory parts to be removed, arguing that the decision should be based on considering also the market demand for those parts as well as the current recycling state of the materials.

Overall, the country is said to have proposed one of the best legislations regarding ELVs. In Spain, ELVs reach ATFs 95% of the time, while other countries struggle to make sure that all vehicles reach ATFs. Additionally, the creation of networks such as SIGRAUTO has helped all actors in fostering a collaborative approach to improving ELV management.

Almost half of the ATFs are part of the SIGRAUTO network as well as all shredding and post-shredding facilities in the country, facilitating the collection and sharing of information as well as in understanding the best strategy to improve the recovery of materials.

4.4. Best Practices in ELV Management

4.4.1 Renault Closed Loop System: The Future is NEUTRAL

Renault has positioned itself as a leader in the circular economy, redefining how resources are utilized and reused in the automotive industry. Since its early partnership with the Ellen MacArthur Foundation in 2010, Renault has embraced circular principles, integrating sustainability into every stage of its operations. This long-term vision shifts away from the traditional linear economic model toward a more resource-efficient framework, addressing material scarcity while ensuring the future of sustainable mobility.

By embedding circular economy strategies across its supply chain, Renault has reduced its environmental footprint while demonstrating the economic benefits of such practices, generating approximately €0.5 billion annually from recycling and remanufacturing. As the first automaker to establish an industrial circular system, Renault continues to expand its initiatives globally, with projects focused on remanufacturing, extending EV battery lifecycles, and developing sustainable mobility solutions.

A major step in this strategy came in 2022 with the launch of The Future is NEUTRAL, Renault's ambitious initiative aimed at achieving resource neutrality in the automotive sector. Recognizing that over 85% of a vehicle's materials consist of metals and plastics, Renault seeks to maximize the recovery of these materials through collaboration with dismantling stakeholders. The goal is to reintegrate ELV-derived materials into new vehicle production and repair processes, reducing reliance on virgin raw materials and minimizing both environmental impact and production costs.

At the core of this initiative is Renault's focus on reclaiming key materials such as steel, aluminum, and plastics. While a substantial portion of the recycled content may not come directly from ELVs—since materials are often sourced from other industries—Renault's closed-loop system still plays a crucial role in reducing material waste and the demand for newly extracted resources. This strategy is particularly vital for lowering emissions and mitigating the environmental costs associated with resource extraction.

Renault also extends circular principles beyond manufacturing into after-sales services, offering remanufactured parts that undergo rebuilding and reconditioning to return them to like-new condition. This includes powertrains, transmissions, and electronic components, contributing to vehicle longevity while reducing waste.

A key aspect of Renault's sustainability efforts is its approach to EV battery lifecycle management. The company repurposes used EV batteries for non-automotive energy storage applications, giving them a second life before they are ultimately recycled. This not only enhances resource efficiency but also supports energy storage solutions for various applications.

By pioneering closed-loop systems and circular economy strategies, Renault sets a benchmark for the automotive industry, showcasing how sustainable practices can drive economic value, lower production costs, and promote responsible resource management.

The Future is NEUTRAL" system relies on various subsidiaries:

- Indra (vehicle recycling): major player in automotive recycling in France, it specializes in recovering ELVs from impound yards, insurers, garages, dealerships, and private individuals, while also offering expert advice on the dismantling process. Established in 1985, Indra has been jointly owned by Renault and SUEZ (a French group specializing in water and waste management) since 2021. Indra operates a network of

370 ATFs and processed 600,000 ELVs in 2023, generating a turnover of €56 million. With an R&D department at Indra Re-Source and a dedicated parts reuse system called Precis, Indra stands out as one of the most advanced ATFs in France and Europe.

- **Gaia** (closed loop materials sourcing): fully owned by Renault, Gaia manages the supply side of the system. Gaia focuses on recycling copper and polypropylene and extracting precious metals like platinum, palladium, and rhodium. It also reuses parts from dismantled vehicles and overstock from after-sales and end-of-series vendors. Additionally, Gaia operates the Expert Battery Repair Center (CERBF), where it extends battery life. In 99% of cases, batteries are repairable. However, when their remaining capacity is insufficient for automotive use, they are prepared for a second life.
- **Boone Comenor** (production scrap recycling): held at 33% by Renault, jointly with SUEZ, Boone Comenor Metalimpex specializes in the collection, sorting, and recovery of metal waste for the industrial sector. It serves industries such as automotive, railways, aerospace, foundries, and steel manufacturing.
- **The REMAKERS** (remanufacturing): Originating from Renault Group's parts remanufacturing at the Flins ReFactory, The REMAKERS is responsible for managing the usage phase within the system. The main focus of this subsidiary is on parts remanufacturing and extending the life of vehicles, with an offer particularly suitable for older vehicles. These remanufactured parts are complementary to original parts and are designed to provide the same level of quality, but with the added benefit of being more environmentally friendly and cost-effective for the customer. The range includes over 11,000 items, from mechanical components to electronic parts, as well as Europe’s first offering for electric vehicles. Launched in 2020, Refactory is the first European circular economy factory, along with an Open Innovation Hub and a future University campus. In November 2021, Renault launched another circular economy factory in Seville (Spain) with a targeted roll-out between 2022 and 2024.
- **Mobilize** (battery 2nd life): Mobilize leverages second-life batteries to create energy storage units as part of various projects. These include mobile, modular storage units that replace polluting generators and large-scale stationary storage. Mobilize has already achieved over 20 MWh of storage capacity in battery farms in France and Germany.

Renault has also entered into a strategic partnership with Veolia and Solvay to drive the circular economy of electric vehicle (EV) battery metals in Europe through closed-loop recycling. This collaboration leverages Renault's leadership in EV battery lifecycle management, Veolia's extensive experience in lithium-ion battery dismantling and recycling using hydrometallurgical processes, and Solvay's expertise in the chemical extraction and purification of battery metals.

By improving mechanical and hydrometallurgical recycling methods, the partnership aims to extract and purify critical EV battery metals, such as cobalt, nickel, and lithium, into high-purity forms, ready for reuse in new battery production. This initiative not only ensures a sustainable supply of essential materials but also significantly reduces the environmental impact of future EV batteries. With the global EV market projected to grow from 10 million vehicles in 2020 to over 100 million by 2030, the group has set a target to recycle 80% of materials back into new battery production in Europe by 2030. This bold commitment supports Renault's broader ambition to achieve carbon neutrality in Europe by 2050, reinforcing its leadership in fostering a circular and sustainable automotive industry.

Furthermore, Renault's approach goes beyond just partnerships. By holding ownership stakes in key entities such as THE REMAKERS, Indra, Gaia, and Boone Comenor, Renault is deeply integrated into extending vehicle lifespans, recycling materials, and remanufacturing parts. This strategy of direct ownership ensures full control and integration at each step of the process, an approach that sets Renault apart from other OEMs that may only engage in collaborative efforts without making such significant investments. Renault's comprehensive commitment to the circular economy establishes a new industry benchmark for genuine, transformative action in the automotive sector.

Renault's dedication to the circular economy is also reflected in the design of its vehicles, such as the All-new Renault Scénic E-Tech electric. This model incorporates a minimum of 18% recycled materials and 24% materials sourced from the circular economy. These materials include those recycled in compliance with the ISO 14021 standard, as well as production offcuts and scraps reincorporated into manufacturing processes at industrial sites, like scrap aluminum and plastic bottles. In total, nearly 40 kilograms of recycled plastics are used throughout the vehicle. Furthermore, 90% of the vehicle's mass, including the battery, can be recycled via established industrial processes.

Adopting eco-design principles, Renault has eliminated leather from the vehicle's interior, replacing it with recycled materials that reduce the carbon footprint without compromising on quality or comfort. The seat textiles now feature up to 100% recycled material, and the dashboard structure and carpets are crafted from recycled or bio-based materials.

Renault's forward-thinking approach extends beyond vehicle production. By refurbishing spare parts and reusing batteries, the company aims to achieve 33% of recycled materials sourced from its own vehicles by 2030. These extensive efforts significantly reduce the reliance on virgin raw materials, minimize the carbon footprint of its vehicles, and address resource scarcity. Renault's holistic approach sets a compelling example for the automotive industry, urging other players to join the movement toward a sustainable, resource-efficient future.

4.4.2 BMW HV batteries closed-loop recycling system

Assuring a sustainable supply of CRM, such as nickel, lithium, and cobalt, which are necessary for HV batteries, is a major obstacle in the shift to EVs. BMW has addressed this by putting in place a closed-loop recycling system in China that recovers materials from production rejects, test vehicles, and, eventually, ELVs.

By reintegrating these recovered materials into the manufacturing of new battery cells, reliance on primary raw materials is decreased, and CO_2 emissions are reduced by 70% in comparison to the extraction of fresh materials. This program guarantees the smooth tracking and recycling of batteries and complies with China's regulatory need for a high-voltage battery tracing system.

Moreover, BMW evaluates the potential for second-life applications, repurposing batteries with residual capacity for energy storage and industrial use before they enter the recycling phase. This strategy is part of BMW's broader circular economy commitment, encapsulated in the "Re:think, Re:duce, Re:use, Re:cycle" framework, and supports the company's long-term goal of achieving climate neutrality by 2050 under the Race to Zero initiative.

With Europe also tightening its Battery Regulation, understanding how such closed-loop models can be adapted to the European ELV ecosystem is crucial. As EV adoption accelerates, the projected increase in retired high-voltage batteries highlights the urgency of integrating circular economy principles into ELV dismantling processes. Future policy frameworks will need to ensure that high-value materials are effectively recovered, contributing to both resource security and environmental sustainability.

BMW has also recently expanded its closed-loop battery recycling efforts through a strategic European partnership with SK tes, announced in November 2024. This collaboration focuses on efficiently recovering cobalt, nickel, and lithium from EoL batteries, which are then reintegrated into the production of BMW's sixth-generation drive train batteries.

The recovered materials maintain high levels of purity when hydrometallurgical processing is used, which lowers the carbon footprint of battery manufacture and the demand for virgin raw materials. By 2026, BMW intends to expand this program outside of Europe to North America, demonstrating its dedication to a globally sustainable supply chain.

The company's Recycling and Dismantling Centre, which has been refining circular economy strategies for over three decades, continues to play a crucial role in designing vehicles with EoL recovery in mind. These efforts not only strengthen resource efficiency but also enhance BMW's supply chain resilience, positioning the company at the forefront of sustainable innovation in the automotive sector.

Beyond battery recycling, the BMW Car2Car project represents another significant effort in advancing circular economy practices within the automotive industry. Unlike Renault's The Future is NEUTRAL, which is highly integrated into Renault's own supply chain, BMW's initiative emphasizes cross-industry collaboration by working with recycling companies, material processors, and research institutions.

A key aspect of Car2Car is its focus on improving the quality and purity of secondary raw materials, including aluminum, steel, glass, copper, and plastics, through AI-driven sorting technologies and automated dismantling. The use of laser-induced plasma spectroscopy and other advanced detection methods aims to create high-purity material streams suitable for reuse in new vehicles, thus addressing one of the primary challenges in ELV recycling - contamination and material degradation.

Supported by €6.4 million in German federal funding, the project also seeks to reduce the automotive sector's dependency on virgin raw materials and imported resources, aligning with broader EU sustainability goals.

While still in development, Car2Car has the potential to scale up ELV recycling efficiency across a wider range of materials, reinforcing the industry's shift towards a more resource-efficient future.

5. Gaps and Challenges in ELV Management

5.1. Implementation Gaps in the ELV Directive

While the ELV Directive has established a clear framework for the management of ELVs across the European Union, its effective implementation varies significantly among Member States. The efficiency and success of this framework depend largely on how proactively each country adapts the Directive's provisions within their own legislation and incorporates them into their existing waste management systems.

Factors such as national administrative resources, economic constraints, and historical practices play a crucial role in shaping how well the Directive is implemented and its impact on the overall ELV supply chain.

Countries like Belgium and Germany reported a share of 87,7% and 86,8% respectively for reuse and recycling, and 90% and 89,5% for reuse and recovery already in 2006, exceeding the target set by the Directive at the time.

By the mid-2000s, Belgium had developed a structured ELV management system, with the Flemish Region taking a proactive role. The free take-back system was fully implemented by 2006, ahead of the EU Directive's requirement, ensuring that vehicle owners could dispose of their ELVs without cost. FEBELAUTO, the national coordinating body, created a network of treatment facilities, which expanded significantly, handling over 131,000 vehicles in 2006 compared to 38,000 in 2002.

To improve recycling performance, Belgium introduced the EMS system for tracking ELV data, incorporated best practices into environmental permits, and worked with insurance companies to enhance collection rates.

As for Germany, the implementation of the Directive showed mixed results in the first years. The 2002 transposition of the Directive through the ELV Ordinance initially faced scrutiny from the European Commission, mainly due to scope limitations and cost-free take-back issues. Germany swiftly addressed these concerns and aligned to the standard set by the Directive.

While the situation reported in 2006 is positive, the country struggled in the previous years to reach the targets, a situation that was mainly due to the high quantity of material that was being landfilled.

To reduce the impact of landfilling, Germany implemented stricter regulations, particularly with the *Abfallablagerungsverordnung* (Waste Disposal Ordinance), which prohibited the landfilling of untreated shredder residues starting in 2005. This was a pivotal move in encouraging better waste treatment and recycling practices and it also aligns with the decision to introduce a similar ban on landfilling in the proposed Regulation.

Countries with the necessary infrastructure and technology for energy recovery will have a significant advantage over those, such as Italy, that lack the systems to recover materials currently being sent to landfills. Furthermore, the ban outlined in the proposed Regulation may force these countries to export waste materials, like fluff, abroad in order to avoid landfilling, further undermining the economic sustainability of the system.

The Directive's requirement for increased levels of reuse and recycling, moving beyond basic scrap metal recycling to include materials like plastics and certain waste combustion processes, has also raised the cost of disposal. Countries that were used to simpler, cheaper disposal methods have faced significant challenges in meeting these new recycling targets, which have proven to be an economic burden for some.

Additionally, the administrative complexity of implementing the Directive is significant. Many countries have had to set up entirely new systems for reporting and certification, including requirements for certificates of destruction and the tracking of vehicles from their EoL to their recycling destinations.

These new responsibilities demand considerable administrative resources, which some countries, particularly those with lower administrative capacity, have struggled to provide. This has led in the past to implementation delays and in some cases, incomplete adoption of the Directive's requirements.

Regarding the 3Rs targets, even if most countries have increased their recovery share during the years, the situation reported in 2022 shows that not all countries are currently meeting the targets that are in force since 2015.

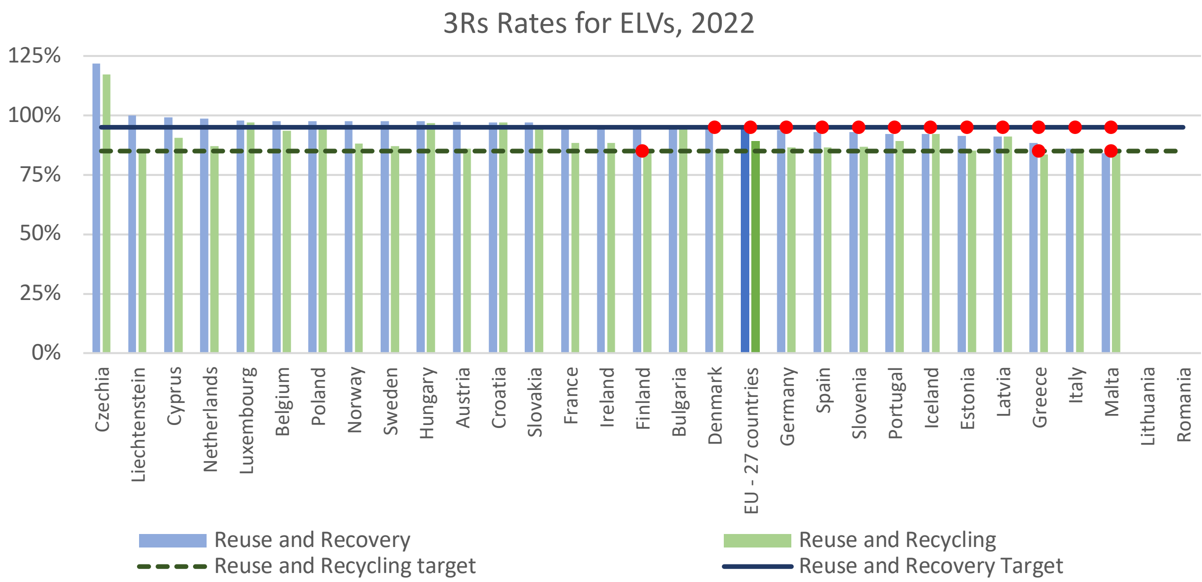

Figure 11. Reuse, recycling and recovery rates for ELVs in 2022
(Source: personal representation of data from End-of-life vehicles - reuse, recycling and recovery, totals [env_waselvt] by Eurostat)

Currently, the reuse and recovery target is the most difficult to reach: 11 Member States failed in reaching the target in 2022. While Lithuania's data is not available for 2022, the country achieved both targets in 2021. Romania's last available data from 2020, shows 85,4% for reuse and recycling and 91,6% for reuse and recovery, therefore achieving just one of the two targets.

Regarding the Reuse and Recycling target, only Finland, Greece and Malta did not meet the target, with Finland is the only country to reach the reuse and recovery target but failing in the recycling side.

Additionally, the way ATFs report the weight of the vehicle at the start of the treatment can impact the reported 3Rs %. The Italian Industrial Association of Auto Recyclers (Associazione Industriale Riciclatori Auto, AIRA) reported in 2018 that most ATFs in Italy were lacking appropriate weighting systems to register the weight of the ELV with the result that many reported an estimated weight based on the registration documents.

While this may apply to ELVs in perfect condition, the same cannot be said when considering damaged vehicles, where parts may be completely or partially missing.

One significant challenge in accurately reporting 3Rs performance is the way ATFs report the weight of vehicles, which can distort the reported percentages. The study conducted on the Fiat Punto highlights the impact of estimating versus measuring the weight of an ELV:

Calculation with weight from registration documents		Calculation with real weight of the vehicle	
940 kg	Mass from vehicle registration document		
75 kg	Passenger weight		
40 kg	Fuel weight		
825 kg	ELV weight recorded by the ATF	**900 kg**	ELV real weight recorded by the ATF
25 kg	Weight of battery, oils and various fluids	25 kg	Weight of battery, oils and various fluids
120 kg	Weight of tyres with rims, fuel tank, reservoir, glass, and catalytic converter	120 kg	Weight of tires with rims, fuel tank, reservoir, glass, and catalytic converter
680 kg	Remaining weight	**755 kg**	Remaining weight

Table 10. Calculation reported from weight comparison
(Source: results reported by AIRA, 2018)

This study, which compares estimated and real vehicle weights, shows that a difference of 75 kg (9.1% of the reported weight) could be considered unaccounted material for recovery. Such discrepancies in weight reporting can contribute to inaccurate reporting of 3Rs performance at the national level.

Additionally, the lack monitoring by authorities, especially in countries with a large number of ATFs, increase the probability of an improper dismantling of vehicles which in turn affect the shredding and recycling of the various materials.

While differences in technologies and reporting methods affect the 3R rates reported to the European Commission, it's important to note that these percentages refer only to vehicles treated in authorized treatment facilities (ATFs), a situation that does not always apply to the millions of ELVs annually in circulation.

In fact, many countries deal with vehicles that are treated in unauthorized facilities or disappear without a trace. These vehicles may be deregistered but not provided with a Certificate of Destruction (CoD). In 2008, Oeko-Institut estimated that 4.1 million vehicles were unaccounted for, and by 2014, this figure had increased to 4.66 million. More recently, an analysis of the change in vehicle stock and the inflow of ELVs revealed that 3.4 million vehicles went missing out of 6.1 million ELVs treated.

While some countries, like Spain, have advanced in increasing the share of vehicles reaching ATFs by incorporating it into their legislation, this is not the case for all. The ELV Directive leaves Member States to "take the necessary measures to ensure that all end-of-life vehicles are transferred to authorised treatment facilities".

To address this, the proposed ELV Regulation introduces an article requiring vehicle owners to deliver their ELVs to an ATF and present a CoD to the relevant registration authority. This CoD is also recognized across Member States, facilitating the export of vehicles between countries.

5.2. Industry Challenges: Design for Dismantlability

5.2.1 Barriers to integrating dismantlability in vehicle design

One of the proposed solutions to improve the management of ELVs is for OEMs to integrate Design for Circularity (DfC) into vehicle production. By doing so, vehicles are designed to simplify the removal of parts, which not only reduces the operational burden on ATFs but also increases the purity of recovered materials, ultimately decreasing the overall dismantling cost.

DfC encompasses various strategies already evident in the automotive sector. For instance, the removal of hazardous substances, regulated by the ELV Directive, has been a primary focus. This Directive prohibits heavy metals such as lead, mercury, cadmium, and hexavalent chromium, while also intersecting with the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation.

Although these measures impose additional regulatory burdens on OEMs, the clarity of these bans has helped ensure that hazardous substances do not compromise the recycling of parts and components. As a result, the sector has made significant progress in safely managing hazardous materials.

However, other aspects of DfD, such as designing vehicles that facilitate easier dismantling or increasing the use of recycled materials, are not yet clearly addressed in the Directive and as such, any action taken to improve the dismantlability of vehicles is voluntary.

As Williams et al. (2020) note in their evaluation of the ELV Directive, the current provisions are insufficiently detailed or measurable, preventing substantial improvements at the EU level. Article 4(b) of the Directive states that new vehicles should “take into full account and facilitate the dismantling, reuse and recovery, in particular the recycling, of end-of-life vehicles, their components, and materials” but it does not outline any measurable criteria for assessing these goals. This lack of specific, enforceable targets has made it difficult to create clear incentives for OEMs to adopt practices that would facilitate dismantling or increase the use of recycled materials.

The evaluation concludes that the car industry has not yet become sufficiently circular, despite the Directive's intentions. Without further clarity and concrete measures, the transition to a more sustainable and circular automotive sector will continue to be slow.

The issue is addressed in the proposed ELV Regulation through Article 7, which provides a more specific and enforceable framework for designing vehicles in a way that facilitates dismantling and the recovery of key parts. The Article requires vehicles to be designed:

- To avoid hindering the removal of parts and components listed in Part C of Annex VII by ATFs during dismantling.
- To ensure that, as regards joining, fastening, and sealing elements, the vehicle is designed in such a way that it allows the non-destructive removal and replacement of electric vehicle batteries and e-drive motors.

While the Regulation proposes clearer solutions, it is still unclear how to evaluate whether the design of the vehicle hinder the removal of other parts as well as how to ensure that joining, fastening, and sealing elements allows parts to be removed in non-destructive way by ATFs, especially since this may depend on the type and number of tools available to ATFs.

Unclear evaluation methods also impact the enforceability of such articles increasing the risks that such measures can potentially lead to partial or inconsistent implementation by OEMs.

Additionally, the design for dismantlability must also find new innovative ways to make sure that the time spent on dismantling can actually be reduced by focusing also on how the assemblies and sub-assemblies in the vehicles are organized as well as the number and type of connections needed to link the various areas of the vehicles.

Lower dismantling time can in fact induce the ATF to remove a higher quantity of parts and material, or at least reduce the cost to comply with the proposed ELV Regulation, where the category of parts and components proposed to be removed increases to 19.

One crucial insight comes from an analysis on the barriers for remanufacturing by Hatcher et al. (2011). While the paper focuses on remanufacturing, it can be said that since dismantling is a necessary step for a part to be retrieved and later remanufactured, the challenges highlighted, such as the lack of design considerations for ease of disassembly, are equally relevant to ELV dismantling and material recovery.

This logic of remanufacturability, where products can be remanufactured only by chance rather than by deliberate design, is equally prevalent in the automotive sector. Vehicles that could otherwise benefit from remanufacturing processes, such as part reuse, are frequently designed in ways that complicate dismantling or make it inefficient, leading to missed opportunities for recycling and recovery.

Additionally, the lack of lifecycle thinking in vehicle design, where environmental impact and EoL recovery are considered early on, and dedicated methodologies compounds this issue. Without a shift towards considering dismantlability as an integral part of the design process, automotive companies risk missing the environmental and economic benefits that could be achieved through improved ELV management, including remanufacturing, which could increase demand for reusable parts in ATFs.

The early consideration of dismantling and remanufacturing in vehicle design is critical to optimizing the EoL management process. A recent industrial pilot study demonstrated that by incorporating dismantling and recovery practices in the design phase, heavy vehicle manufacturers can significantly enhance the feasibility and profitability of remanufacturing efforts (Saidani et al., 2020).

The study found that certain vehicle components, when designed for easier removal, allow for more efficient recovery, thereby contributing to a more effective circular economy (CE) strategy. Additionally, the introduction of a "dismantling manual" and more detailed guidelines for remanufacturing practices was identified as an effective way to streamline these processes. These steps, aimed at improving disassemblability, not only facilitate recovery but also enhance the potential for remanufacturing key components.

The imperative for sustainable vehicle design has driven significant research into incorporating dismantlability considerations at the early stages of product development.

For example, studies have highlighted that sustainable practices, including material homogeneity and streamlined disassembly, are crucial for reducing both recycling complexity and environmental footprints (Mayyas et al., 2011]). Similarly, eco-design approaches that advocate for the use of single materials in vehicle interiors can simplify the separation and recycling of components, thereby supporting circular economy strategies (Staniszewska et al., 2020).

In parallel, the development of systematic evaluation methods has provided designers with quantitative tools to assess disassemblability. The ease of disassembly method (eDiM), for instance, utilizes a database of disassembly times derived from work measurement theory to quantify the effort required for dismantling various product components.

Such methodologies offer transparent, repeatable frameworks that are applicable across a range of products, from consumer electronics to automotive components, thereby assisting manufacturers and policymakers in enforcing design standards that facilitate repair, reuse, and recycling (Vanegasa et al., 2018).

Complementary to this, critical reviews of disassemblability in vehicles have stressed that early incorporation of DfD principles not only enhances material recovery but also reduces overall recycling costs by considering factors such as component accessibility, force requirements, and tool dependencies (Go et al., 2010).

Economic feasibility is also another essential consideration. Optimization tools for design for recycling (DfR) have been developed to balance disassembly costs with recycling rates. For example, studies have demonstrated that achieving higher recycling rates may necessitate design modifications, such as replacing fixed connections with fast-removal techniques, that can lower disassembly times, albeit sometimes at a financial cost.

These findings emphasize the need to align design choices with the capabilities of local recycling infrastructures to maximize both environmental and economic benefits (Ferrão and Amaral, 2006).

In summary, incorporating dismantling considerations into vehicle design requires a multifaceted approach that spans advanced materials, systematic evaluation methods, and emerging technologies. By integrating these elements, from smart materials and AR-enhanced disassembly, automotive design can effectively balance the demands of environmental sustainability, economic viability, and operational efficiency.

5.2.2 Current state of the automotive sector

When we look at the current state of the sector in terms of DfD and introduction of recycled material in vehicles, public information available shows that additional improvements are still to be made but that the sector is aware of the impact of circular economy measures for the supply chain.

By looking at the initiatives from Toyota regarding increasing the ease of removal of parts, the initiatives focus on:

- Adding special markings on components that were particular targets of dismantling such as markings to show hoist positions and areas where it’s easier to remove the part
- Markings on heavy parts such as battery for BEV and cell fuel stacks to indicate the center of gravity to enable a balanced transportation
- Incorporation of V-shaped grooves in its instrument panels that indicate specific parts that can be removed just by pulling, without requiring special tools or complex procedures.
- Using a wire harness pull-tab grounding terminal structure, resembling the ring tab of an aluminum can, is adopted to enable grounding parts to be separated and dismantled simply by pulling.
- Using visible tape on wire harness in locations where it can be pulled of more easily
- Design the wire harness to enabling pulling it out without making contact with other parts as far as possible.

Increasing the presence of markings and tapes to facilitate the visual recognition for the operator of critical removal points is a fundamental part of Design for Dismantling (DfD), as it ensures that any improvements in design are easily seen and recognized by the operator even without the manuals provided by the OEM.

The BMW Group has also actively participated in the dismantling of their vehicles, thanks to research lab and recycling facility called BMW Group Recycling and Dismantling Centre (RDC) where vehicles are evaluated before the series development begins.

Such center has also developed tools to ease the dismantling of vehicles such as a special device for removing shock-absorbers oil, single equipment for discharging pyrotechnic components, optimised hydraulic shears to efficiently dismantle components such as wire harness and catalytic converter as well as a device to recover glass.

While major European OEMs such as Volkswagen, Stellantis and Mercedes Benz have been managing their ELVs through their respective networks, active participation in the dismantling area is often limited.

In light of the new ELV Regulation, which added a target for the inclusion of recycled plastic from ELVs into new vehicles, it will be crucial for each OEM to evaluate their current practices and enhance collaboration with dismantling and recycling facilities.

The ability to increase the recovery of valuable materials and ensure that these are effectively reintegrated into the manufacturing process will require both innovation in vehicle design and a stronger commitment to standardized dismantling practices.

While the inclusion of DfD features in vehicles is currently limited, the adoption of recycled material is being gradually applied to vehicles. While the main areas of adoptions are usually in the interiors parts such as seats and instrument panels, OEMs are adding presence of recycled plastic also in external parts such as bumpers.

The reporting of recycled content (RC) by OEMs in Europe reveals significant inconsistencies and limitations. By analyzing publicly available data on the top-selling vehicles in 2024, reported in Table 11, it becomes apparent that while some OEMs provide detailed information on the use of recycled materials, others either fail to report any data or only offer partial details.

Top sold car 2024	Reported Recycled Content
Dacia Sandero	Not reported.
Renault Clio	Only Alpine seats specify 65% recycled PET
Volkswagen Golf	28% of textiles and 6% of thermoplastics made from recycled materials
Tesla Model Y	Not reported.
Volkswagen T-Roc	Not reported.
Peugeot 208	30% recycled and natural materials There recycled materials are used in polypropylene parts like spoilers, airbag components, fenders, front/rear bumpers, and polyamide parts like the wheel covers, intake manifold, and fan-motor assembly
Toyota Yaris Cross	Not reported.
Skoda Octavia	33% recycled materials (including steel, aluminium, plastics, glass, and insulation materials). These recycled materials are used in components such as underbody panelling, wheel arch liners, boot mats, interior trim, and air ducts.

Dacia Duster	The vehicle includes the use of Starkle® (20% reused polypropylene) for parts like side underbody shields, wheel-arch guards, and front/rear skid plates.
Toyota Yaris	Not reported

Table 11. Reported recycled content for top sold cars in 2024
(Source: Recycled content data compiled from various sources; see bibliography for full references.)

The reported recycled content across the top 10 sold vehicles in 2024 varies widely, with figures ranging from zero (where not reported) to as much as 33% in the Skoda Octavia, which includes recycled materials in components such as steel, aluminum, and plastics.

For example, the Renault Clio specifies that 65% of the seats in the Apline version are made from recycled PET, but this level of detail is limited to a single component and model. In contrast, other vehicles such as the Dacia Sandero and Tesla Model Y report no information on recycled content at all.

The Peugeot 208 reports 30% recycled and natural materials, specifying the use of recycled polypropylene and polyamide in parts like bumpers, airbag components, and fenders. However, such detailed breakdowns are still limited to select materials and parts, typically those less visible or critical to the vehicle's structure, such as interior components and bumpers.

In addition to analyzing the top-selling vehicles in 2024, some of which started production prior to 2024, it is valuable to assess vehicles unveiled in the same year, as they may provide insight into the automotive industry's future direction regarding recycled material adoption.

Model	Reported Recycled Content
Dacia Bigster	The vehicle includes the use of Starkle® (20% reused polypropylene) for parts like wheel arches and side skirts
Fiat Grande Panda	Incorporates 20% recycled content in its interior blue plastic parts, made from non-recyclable plastics recovered from 140 beverage cartons per vehicle
Renault 5	It features 23% recycled materials in its interior, including fabrics made from recycled materials and plastics used in the console and dashboard. Additionally, 50% of the materials in the trunk are recycled components
Ford Capri Select	The interior uses Nordic Swan Ecolabel-certified materials, including 20% recycled plastics from ocean waste.
Alfa Romeo Junior	0%
Opel Frontera	The seat fabrics are available in a fully sustainable recycled material
BMW X3	The vehicle features seats and upholstery made from the standard Econeer fabric, which is composed of 93% recycled secondary material. For Interior Surfaces, an optional instrument panel made from recycled polyester. Additionally, light-alloy wheels are made from 70% secondary aluminum.

Table 12. Reported recycled content for newly released vehicle
(Source: Recycled content data compiled from various sources; see bibliography [] for full references.)

Table 12 presents the reported recycled content in several recently unveiled models.

While some manufacturers show promising figures, others fall short in reporting or integrating recycled materials into their models.

Some vehicles, like the Fiat Grande Panda and Dacia Bigster, incorporate around 20% recycled content in specific parts, such as interior plastics and exterior components. However, these figures remain relatively modest.

In contrast, the Renault 5 shows a more comprehensive approach, with 23% recycled content in its interior and 50% in the trunk, reflecting a broader commitment to sustainability.

The BMW X3 stands out with 93% recycled material in its seat upholstery and 70% in its light-alloy wheels, setting a high standard for recycled content integration. Meanwhile, the Ford Capri Select uses 20% recycled plastics from ocean waste, showcasing a focus on environmental issues beyond traditional recycling efforts. However, Alfa Romeo Junior reports no recycled content, highlighting inconsistency in OEM practices.

5.3. Infrastructure and Technology Limitations

5.3.1 Uneven technological adoption among ATFs

The ELV Directive has significantly shaped the dismantling process across Europe, making it the norm for the approximately 14,000 Authorized Treatment Facilities (ATFs) to engage in standardized processes, from depollution to part recovery. This evolution has led to increased scrutiny of ATFs, particularly since they're the first step in the ELV supply chain. In recent years, attention has been placed on how different ATFs adopt technology and follow standardized processes, with some ATFs excelling and others lagging behind.

Among the most advanced ATFs in Europe, Indra and Pollini serve as prime examples of how technological integration and process optimization can enhance ELV treatment. These facilities have implemented structured dismantling workflows, tracking systems, and additional recovery steps that set them apart from the industry norm. Their processes illustrate the potential efficiency gains that can be achieved when dismantling is approached with a methodical and technology-supported strategy.

At Indra, vehicles are processed through a dismantling line, a rarity among ATFs, where each car moves sequentially through several specialized stations. The process begins with an operator performing an initial vehicle check, identifying the car through its VIN, and assessing the current market demand for its parts. At the same time, the integrated inventory management system is used to verify whether parts from the same vehicle model are already available in stock. This allows for a more strategic dismantling approach, ensuring that components with high reuse potential are prioritized while avoiding unnecessary removals. Smaller ATFs, where such tracking systems are absent, often operate on a less selective basis, dismantling parts without the same level of strategic oversight.

Parts that are needed to be removed are flagged in their system which can be visualized in every station on the respective monitor which is visible for the operator working in the station.

Once the airbags are deployed, the vehicle enters the dismantling line, where operators progressively remove different components. The process starts with the removal of tyres and mudguards, followed by doors and windows, before moving on to the depollution stage, where fluids are drained, and the SLI battery is extracted. Other external and internal components, including plastics, are separated for recovery. Then, a tilting machine is used to rotate the vehicle and to allow full access to the underbody, making it easier to remove key parts such as the catalytic converter. Finally, after disconnecting all powertrain connections, the engine is extracted and further dismantled for part recovery.

The dismantled car is then pressed and ready to be recovered for shredding.

The polypropylene removed and sorted from dismantling is also shredded already at their plant through a shredder which also perform a separation of plastic from metal residues. The plastic chips, resulting from the shredding, permits to increase the efficiency of transportation and are then sent to a processor that will wash and granulate the material and then press the material for recycling.

Also Pollini follows a similar attention in the dismantling of vehicles, by reusing also fluids and liquids when possible and by making sure that materials are separated and stored correctly.

Both ATFs have also developed dedicated procedures for handling batteries from BEVs and HEVs. Batteries are neutralized and stored separately, minimizing safety risks. However, the reusability of these batteries remains a challenge, as it is difficult to assess their condition, particularly when they come from damaged vehicles. As a result, most of the recovered batteries are still directed toward recycling rather than reuse.

Even by removing a large number of components and materials, both ATFs process a high number of ELVs every day: Indra with one line is capable of processing 25 ELVs/day while Pollini reaches 80 ELVs/day with its numerous dismantling stations.

These examples highlight how structured dismantling methods and technological support can lead to higher recovery rates, better material sorting, and ultimately, a more effective circular economy for ELVs.

Lower-quality ATFs, often operating with limited resources, prioritize dismantling parts with high market demand alongside those mandated by the Directive. As a result, materials such as plastic, glass, and copper from wire harnesses are frequently left on the vehicle. Once crushed and sent to the shredder, these materials contribute to contamination, reducing the efficiency of material recovery.

The absence of standardized procedures and safety guidelines further complicates dismantling, as parts may be removed without following OEM recommendations. Additionally, the lack of technological support increases the risk of data loss during dismantling, leading to inconsistencies in reporting and potential inefficiencies in material tracking.

The proposed ELV Regulation is set to significantly impact these ATFs by expanding the list of mandatory parts for removal, including components with low market demand. This shift presents a challenge: if smaller ATFs fail to improve their efficiency, dismantling costs may outweigh the revenue generated from reuse and recycling. In the worst-case scenario, this could lead to a decline in the number of ATFs operating after the Regulation's implementation.

Currently, the reuse market generates the highest profits, with used parts selling at approximately half the price of new ones. To ensure the survival of small ATFs, legislative measures that promote higher reuse rates, such as incentivizing the use of second-hand parts in repair shops, could strengthen the dismantling business.

Additionally, in countries like France, Italy and Spain where the number of ATFs is particularly high, the role of the authorities will be fundamental to make sure that all types of ATFs comply with the articles from the proposed ELV Regulation.

In countries like France, Italy, and Spain, where the number of ATFs is particularly high, regulatory authorities will play a key role in ensuring compliance with the proposed ELV Regulation. Furthermore, since the new removal requirements will take effect before Design for Dismantling (DfD) improvements are fully integrated into new vehicles, ATFs will continue to process ELVs with designs similar to those they have handled for the past two decades.

5.3.2 Infrastructure gaps affecting recycling and material recovery

The adoption of recent technologies for recycling and material recovery in the ELV sector is still highly dependent on infrastructure and technological capabilities, which vary significantly across EU Member States. The EU ELV Directive sets ambitious recovery targets, particularly for material and energy recovery. However, the efficiency of recovery processes often hinges on the infrastructure in place, which is uneven across the region.

One of the most pressing issues is the dismantling process: vehicles are often only partially dismantled before being shredded, which directly impacts the shredding process and the contamination of materials. The new ELV Regulation attempts to address this by increasing the burden on ATFs to dismantle vehicles more thoroughly before shredding. However, the burden on ATFs will likely increase, while the potential for more efficient separation during dismantling will benefit shredders by reducing contamination and mitigating material loss through ASR formation. While these regulatory changes aim to improve dismantling, post-shredding technologies are less emphasized, despite their potential to improve material recovery.

Technologies like density separation and infrared laser systems for separating plastic fractions from ASR are already being used in some facilities. These systems are effective in increasing the recovery of plastics and enhancing their purity, but their adoption is still limited across Europe. The costs and technological challenges of scaling these technologies remain barriers. While the EU's ELV Regulation has a focus on improving material purity at the dismantling stage, there is a lack of emphasis on enhancing post-shredding technologies, which could significantly contribute to better material recovery.

Energy recovery from ASR also presents challenges, particularly in countries like Italy, where the technology and infrastructure to efficiently recover energy from ASR are lacking. As a result, the preferred method in these countries remains landfilling, leading to a loss of around 15% of recyclable materials. This discrepancy in infrastructure and technology creates significant gaps in the ability to meet the EU's recovery targets for ELVs. For example, in Italy, ASR disposal through incineration or energy recovery is not yet widespread, resulting in higher levels of waste going to landfills instead of being processed for recovery.

The EU allows Member States to determine their approach to landfilling, with some prohibiting the disposal of untreated SLF/SHF in landfills, while others permit it, particularly for road construction. According to consultations with Member States in preparation for the proposed ELV Regulation, six countries now prohibit the landfill disposal of untreated SLF/SHF, while others still permit it. These discrepancies indicate that regulatory pressure has been instrumental in pushing for better disposal practices in certain Member States, which has contributed to higher recycling rates.

In summary, infrastructure gaps in post-shredding and energy recovery technologies are a significant barrier to achieving ELV recycling targets. Addressing these gaps requires not only improving the current infrastructure but also increasing the adoption of new technologies at both the dismantling and shredding stages. However, much of the focus remains on dismantling procedures rather than improving the technologies that operate later in the recovery chain.

6. Analysis and Insights

6.1. Impact of Current Gaps on Circular Economy Goals

The gaps identified in Chapter 5 have significant implications for achieving the circular economy goals in the automotive industry, particularly regarding recycling and reuse targets set by both national and EU regulations. These gaps hinder the progress toward sustainable practices and reduce the effectiveness of policies designed to promote a circular automotive economy.

6.1.1 Dismantling Barriers and Material Recovery Challenges

The lack of standardization in dismantling procedures is a key challenge for meeting recycling and reuse targets. While initiatives from OEMs, such as Toyota’s and BMW's efforts to improve dismantling processes through clear markings and dedicated tools show promise, these practices remain limited across the sector.

As noted in Chapter 5, the addition of markings and visual indicators by OEMs, alongside technological support at dismantling stations, would improve the efficiency of the dismantling process. However, the inconsistency in the use of platforms like IDIS (International Dismantling Information System) and technological tools at ATFs across Europe remains a problem.

Not all ATFs have access to the necessary technological tools to streamline disassembly, which in turn reduces the potential recovery of recyclable materials. Additionally, research into advanced disassembly methodologies shows that technologies such as Shape Memory Alloys (SMA) and Shape Memory Polymers (SMP) could enhance disassembly efficiency.

These materials enable the release of fasteners through external stimuli (such as heat or electrical current), leading to reductions in disassembly time by up to 55%. However, challenges such as high costs and fabrication complexities mean that these systems are not yet widely adopted.

The lack of technological infrastructure and efficient disassembly systems prevents the full recovery of valuable materials, which slows the progress toward meeting recycling and reuse targets set in the Directive by all Member States.

6.1.2 Inconsistent Reporting of Recycled Content

A significant issue that also impacts the achievement of circular economy goals is the adoption and inconsistency in reporting recycled content in vehicles. As noted in Chapter 5, the recycling rates and the types of materials reported vary widely among OEMs. For instance, while vehicles like the Skoda Octavia and the Peugeot 208 report the inclusion of recycled materials in key parts, others like the Dacia Sandero or Tesla Model Y fail to provide any information on recycled content at all.

This issues, which are also the result of the absence of mandatory targets in the Directive as well as an unstable market for recycled plastic, hampers the ability to track progress on the integration of recycled materials and assess the industry’s overall sustainability performance. Additionally, some OEMs that currently lack the use of RC in parts such as interiors and seats cover, will need to evaluate the current status of the supply chain as well as analyzing the capability of their current suppliers.

Furthermore, the absence of standardized metrics for reporting recycled content across OEMs makes it difficult to compare the effectiveness of different manufacturers' recycling initiatives. The lack of transparency and detailed reporting delays the industry's movement toward circularity, as manufacturers are not incentivized to adopt higher levels of recycled content when there is no standardized expectation for such disclosures.

The proposed target of 25% recycled plastic content in new vehicles is expected to increase the demand for recycled plastic. Although the production of recycled plastic uses 75% less energy than manufacturing virgin polymer, the current market price of recycled plastic remains higher due to limited supply and growing demand. While the mandatory target may drive up prices by stimulating demand, it could also encourage investments in recycling facilities and technologies, thereby expanding the supply of recycled materials.

Although the price of recycled plastic will continue to be influenced by the cost of virgin plastic, which is linked to the fluctuating price of oil, having a more secure demand driven by legislation could also help boost investments in recycling infrastructure. Over time, this could reduce the dependency on virgin plastic and support the growth of a more robust, circular economy.

6.2. Opportunities for Improved Collaboration

One of the most crucial steps in overcoming the gaps and challenges highlighted in Chapter 5 is fostering stronger collaboration between OEMs and ATFs. Such collaboration has the potential to significantly enhance the efficiency and sustainability of the ELV management system, contributing to a more circular economy.

6.2.1 Potential benefits of enhanced OEM-ATF dialogue

The new list of 19 category parts to be removed by ATFs will increase the need for more standardized and easily accessible information regarding vehicle part locations and disassembly steps.

While dashboards are easily accessible, the perimeter of each component may not be known by ATFs in advance. Additionally, parts like dashboards may not be easily extracted from the inside, as they might be difficult to cut before removal. In such cases, additional tools and equipment may be needed to assist the operator.

For example, the use of destructive machines, which tear parts from the vehicle, can ease the removal of such components, but not all ATFs can afford the space and cost associated with these machines.

Furthermore, parts such as electrical and electronic components (e.g., printed circuit boards, photovoltaic panels, etc.) can be extremely difficult to find and extract. These parts are typically integrated into the vehicle and can be recovered only by fully dismantling sensors and cameras, and the number of these components varies significantly depending on the vehicle's technological features.

A stronger collaboration between OEMs and ATFs could improve the quality and consistency of the information shared on platforms such as IDIS. Both parties are deeply invested in vehicle management, but their focus differs—OEMs specialize in assembly, while ATFs concentrate on dismantling.

By working together, OEMs could gradually evaluate the dismantlability of their vehicles, incorporating insights from ATFs and potentially conducting joint studies. These findings could then be incorporated into the vehicle design process, ensuring that future models are easier to dismantle and more efficient in terms of material recovery.

At the same time, increased collaboration between OEMs and ATFs could boost the adoption of parts recovered by ATFs into vehicles through remanufacturing. OEMs could source high-quality parts from ATFs to be remanufactured for use in vehicle repairs, reducing waste and promoting a circular economy.

The added burden on ATFs due to the new list of parts and components to be removed can be mitigated by an increased demand for recovered parts from OEMs. Since OEMs typically have direct lines with repair shops within their network, the demand for reused parts could be more easily managed.

This concept aligns with Article 33 of the ELV Regulation, which calls on Member States to "take necessary incentives to promote the reuse, remanufacturing, and refurbishment of parts and components, whether removed during the use or end-of-life phase of a vehicle." Incentives, such as requiring the offering of used or remanufactured parts to customers or providing economic benefits like VAT reductions, could significantly boost the demand for reused parts and promote a more sustainable circular economy.

In conclusion, the enhanced collaboration between OEMs and ATFs is crucial to improving the dismantling process and achieving the circular economy objectives outlined in the ELV Regulation. The challenges posed by the increasing complexity of vehicle parts and the need for more standardized information can be addressed through joint efforts between these two stakeholders.

By fostering better communication, improving vehicle design for disassembly, and incentivizing the use of recovered parts, both OEMs and ATFs can contribute to reducing waste and promoting sustainability in the automotive sector.

7. Conclusion and Recommendations

This thesis has explored the current landscape of End-of-Life Vehicle (ELV) management in Europe, with a focus on dismantling practices, material recovery, and the regulatory framework driving the shift towards a more circular economy. Key findings highlight the progress made through the ELV Directive and the transition to the ELV Regulation, but also underscore the challenges still faced by stakeholders, particularly Authorized Treatment Facilities (ATFs) and shredders, in achieving the full potential of material recovery and reuse.

While ATFs play a pivotal role in dismantling vehicles and recovering valuable parts, they are often constrained by a lack of standardized information, outdated equipment, and limited incentives to recover parts for remanufacturing. At the same time, shredders, who handle the bulk of the remaining vehicle materials, are central to meeting recycling targets, yet many countries still fail to reach the required recovery rates. This gap in meeting recovery targets is largely due to inefficiencies in the shredding process and challenges in separating materials effectively, which limits the recovery of high-value materials like metals and plastics. Shredders need access to better technology, improved sorting systems, and clearer regulatory guidance to enhance material recovery and help meet recycling goals set by the ELV Regulation.

A significant challenge across both ATFs and shredders is the inconsistency in the reporting and recovery of recycled content. This problem is compounded by a lack of data transparency, which makes it difficult to track the success of circular economy initiatives and to identify areas for improvement. A more standardized and transparent reporting system would not only help regulators monitor progress more effectively but also incentivize all parties to adopt best practices in material recovery. Enhancing collaboration between stakeholders, including OEMs, ATFs, shredders, and recyclers, is critical for improving data flow, sharing insights, and establishing clearer targets and guidelines for material recovery.

OEMs, as the designers and manufacturers of vehicles, must play a larger role in improving the recyclability and dismantlability of their products. Integrating lessons from ATFs and shredders into vehicle design, particularly with regard to ease of disassembly and the use of recyclable materials, will be essential for achieving the long-term goal of a circular automotive industry. OEMs could also improve their support for ATFs by providing standardized information on vehicle components, helping dismantlers identify and remove valuable parts more easily. Additionally, incentivizing the remanufacturing of parts recovered by ATFs could reduce waste and lower the demand for new materials, contributing to a more sustainable system.

For shredders, there needs to be an investment in more advanced technology for separating materials more efficiently. Improved shredding processes, such as the use of advanced sorting and separation techniques, can significantly enhance the quality and quantity of recovered materials. Encouraging the adoption of these technologies through financial incentives or regulatory support could help operators meet higher recovery targets and improve overall material recovery rates. Moreover, enhancing collaboration between shredders and recyclers is vital to ensure that the materials extracted are properly processed and recycled, thus reducing the amount of waste sent to landfills

Incentives for recovery and reuse should be explicitly integrated into regulatory frameworks, particularly for parts remanufactured for resale or reuse. Economic incentives, such as tax reductions or lower VAT on recovered parts, could help stimulate demand for recycled and remanufactured components. Additionally, the introduction of clear recycling targets for shredders and recyclers, as well as requirements for OEMs to source parts from the secondary market, could further stimulate the circular economy. Increased transparency in reporting the percentage of recycled content in new vehicles and parts would also encourage more active participation from all stakeholders.

As the transition to a circular economy progresses, the regulatory framework must continue to evolve to address new challenges and opportunities. The ELV Regulation is an important step, but its success depends on coordinated action among OEMs, ATFs, shredders, and recyclers. Moving forward, a more holistic approach to the entire ELV supply chain—focused on collaboration, innovation, and data transparency—will be essential to achieving the EU's circular economy goals and ensuring that vehicle end-of-life management is both environmentally and economically sustainable.

In conclusion, the automotive industry has made significant strides towards a circular economy, but challenges remain, particularly in achieving higher recovery rates, improving material separation technologies, and fostering stronger collaboration among stakeholders. By addressing the gaps in the current system, enhancing the role of all actors in the ELV supply chain, and implementing the recommendations outlined in this thesis, the sector can unlock the full potential of vehicle recycling, reduce waste, and contribute to a more sustainable future.

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