# ELV Recycling in the EU

## Status Quo vs. Future

A deep dive complementing ERTRAC's roadmap on circularity

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# Disclaimer

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# Acknowledgement

As European Technology Platform, ERTRAC gathers experts from the industry, research providers and public authorities. This roadmap was prepared by the Working Group "Circularity and Competitiveness" with contributions from the following experts:

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# Executive Summary

The European Union's ELV recycling framework is undergoing a profound transformation driven by regulatory pressures, the circular economy agenda, and technological advancements. The current system, governed by Directive 2000/53/EC, largely relies on manual depollution, dismantling, and basic material recovery.

Projections for 2045+ and beyond envision a highly automated and digitized ecosystem, supported by advanced robotics, artificial intelligence, autonomous transport systems, real-time blockchain-based compliance tracking, and cutting-edge recycling and material refining technologies - all working together to enable closed-loop material cycles.

Key differences between the status quo and the future industrial model include:

- Transition from manual to robotic depollution and dismantling.
- Automated, integrated battery recycling with closed-loop reintegration.
- Large-scale, centralized dismantling, shredding and high-tech post-shredder sorting hubs.
- Increased remanufacturing and reuse of parts based on AI assisted state of health-analysis.
- Advanced AI-augmented sorting technologies ensuring high-purity, automotive-grade material recovery.
- Advanced mechanical, chemical, or hydrometallurgical material recycling technologies that can produce affordable secondary materials with characteristics and quality equivalent to those of virgin materials.
- Full material traceability via digital twins and blockchain reporting.
- Near-elimination of residual waste and landfill reliance.
- Integration of autonomous, low-emission logistics systems to minimize transport cost related to circular economy.

Moreover, the proposed future EU flagship Research and Innovation (R&I) project, currently under preparation, is outlined in detail using the visualized scenario to illustrate its key elements and objectives. The specific R&I needs, required to make this flagship initiative a reality, are in the process of being identified and prioritized. The future End-of-Life Vehicle (ELV) system (recycling, remanufacturing, 2nd Life, …) will be a key enabler of the EU's circular automotive economy, as well as for other industries—significantly reducing carbon footprints and dependency on virgin raw materials. The identified process steps are visualized within a scenario to facilitate discussion and support the development of a shared vision among the relevant sectors and stakeholders. Given the crucial role of logistics in future operations, initial considerations have also been included regarding the integration of autonomous transport systems.

In addition, the role of transport infrastructure management will change significantly as well, and it is important that there is alignment needed on both infrastructure and automotive sides. Tools such as LCA will be used increasingly, as will Digital Product Passports. These aspects are not addressed, yet but will be introduced in coming steps.

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# 1 Introduction

End-of-Life Vehicle (ELV) recycling in the European Union is a well-established process governed by the ELV Directive (2000/53/EC) [1]. The current system relies on a network of Authorized Treatment Facilities (ATFs), manual depollution, and component removal, followed by shredding and material recovery. However, the proposed revision of the ELV Directive and emerging technologies will shift the industry toward large-scale, fully automated recycling plants (more general ELV plants) with advanced demanufacturing and material sorting and a focus on closed-loop automotive recycling (but not exclusively).

This document compares the **current process** and a potential, high ambitious **future industrial model** for 2045+ in detail, highlighting the key differences and providing process flow charts for each. The future industrial model for 2045+ should be understood as a high-end scenario, any hybrid scenario in between both ends of the scenarios (today and high end 2045+) is not excluded.

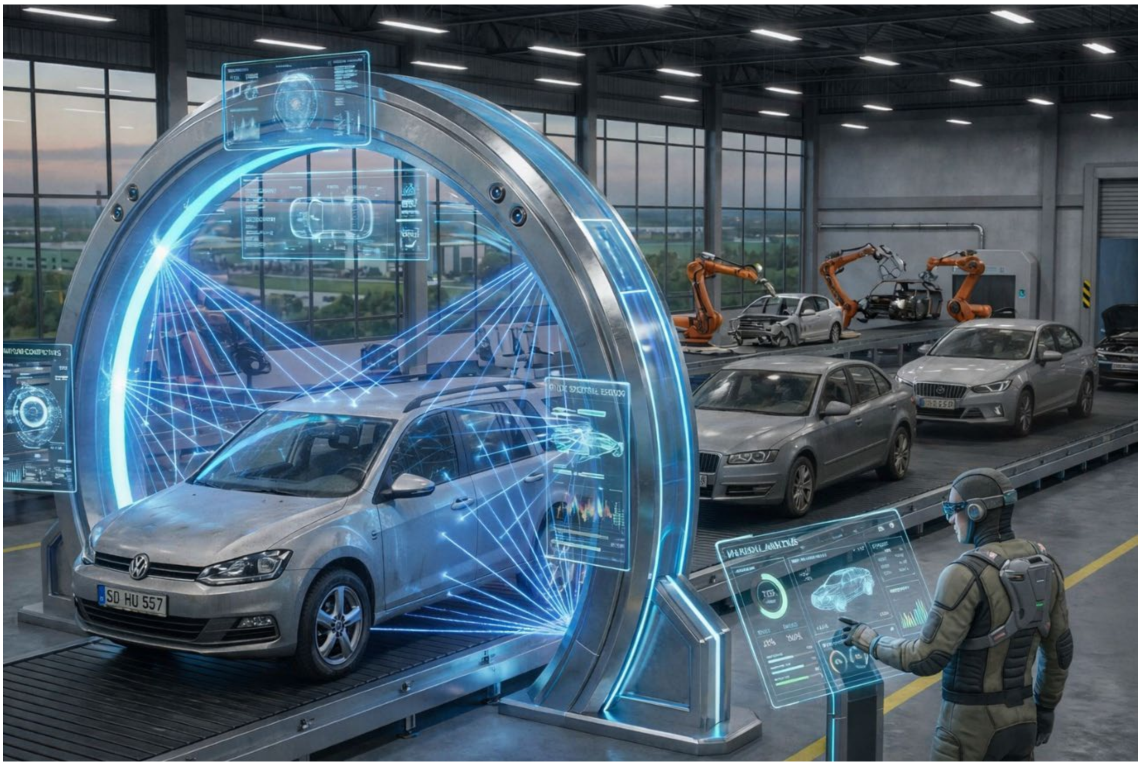


Figure: Diagnostics of in-coming End-of-life vehicles (generated by AI)

# 2 Current ELV Recycling Model and Process

## 2.1 Current Legal Targets for End-of-Life Vehicle (ELV) Recycling

The current legal targets for End-of-Life Vehicle (ELV) recycling are primarily defined at the European level by **EU Directive 2000/53/EC** [2] on end-of-life vehicles. The directive aims to reduce waste and environmental impact while promoting the **reuse, recycling, and recovery** of vehicle materials.

It sets **minimum targets per vehicle by weight**:

- **Reuse & Recycling**: **85%**
- **Reuse & Recovery (including energy recovery)**: **95%**
- **Maximum Disposal (e.g., landfill)**: **5%**

## 2.2 Additional Legal Requirements

- **Producer Responsibility**: Vehicle manufacturers are required to design vehicles in a way that facilitates dismantling, reuse, and recycling of components and materials.
- **Free Take-Back**: Vehicle owners must be able to return their ELVs to certified treatment facilities **free of charge**.
- **Hazardous Substance Restrictions**: The use of materials such as **lead, mercury, cadmium**, and **hexavalent chromium** is strictly limited to reduce environmental harm.
- **Certificate of Destruction (CoD)**: A CoD must be issued when a vehicle is scrapped, ensuring proper deregistration and environmentally sound disposal.

## 2.3 Implementation Across the EU

All **EU member states** are required to implement the directive through **national legislation**. They must also **report their ELV recycling performance** to the European Commission to ensure compliance with EU targets.

## 2.4 Current ELV Recycling Process

### a) Collection

- ELV is delivered to an Authorized Treatment Facility (ATF).
- Vehicle is deregistered and tracked for recycling compliance.

b) Pre-Treatment (Depollution)

- Manual removal of hazardous fluids (fuel, oils, coolants, refrigerants).
- Manual extraction of batteries, airbags, and pyrotechnic devices.

c) Dismantling through an Authorized Treatment Facility (ATF)

- Manual removal of mandatory or valuable parts (engines, wheels & tires, catalytic converters).
- Components sold for reuse or remanufacturing or put into the appropriate circuit for recycling or disposal.
- The ATF issues the Certificate of Destruction (CoD)

d) Shredding

- Hulled vehicle carcass is shredded.

e) Post-Shredder Treatment for material recovery

- Air separation to obtain shredder light and heavy fractions (SLF / SHF)
- Magnetic and eddy current separation to recover ferrous and non-ferrous metals.
- Limited sorting of plastics and reinforced composites.
- Material streams: ferrous metals, non-ferrous metals, automotive shredder residue (ASR).

f) Recycling

- Recovered metals reintroduced to general recycling markets.
- Some plastics are recycled but with significant losses to mixed waste streams.
- Often results in open-loop recycling due to down-graded material quality

g) Disposal

- Residual waste (ASR & SLF) typically landfilled or incinerated.

h) Compliance

- Targets: minimum 85% reuse/recycling and 95% reuse/recovery by weight.

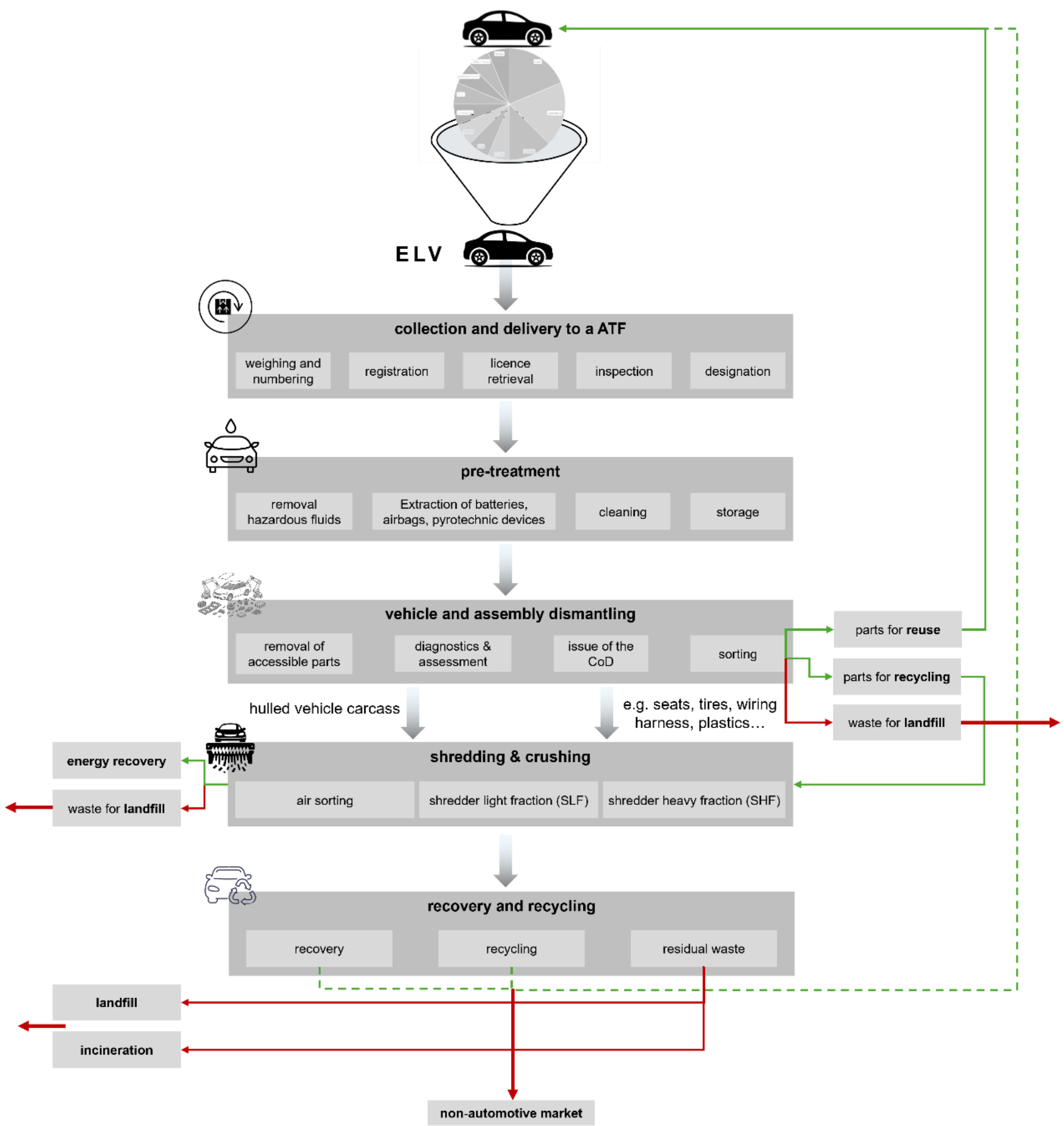


Figure: Flow Chart of the current ELV Recycling Process (inspired by [10 & 11])

# 3 The Road to Net Zero: A Future ELV Recycling Model (Scenario 2045+)

## 3.1 Projected Legal Targets for 2045+

### 1. Future Legal Targets for End-of-Life Vehicle (ELV) Recycling

As of 2025, no official legal targets have been established for ELV recycling in 2045. However, strategic policy developments—particularly the Clean Industrial Deal [2], the Circular Economy Action Plan [3], and proposed revisions to the ELV Directive [4] (which should enter into force in 2026)—strongly suggest the direction of future legislation. Among other, the Clean Industrial Deal asking for a circular material rate of 24% by 2030 and the revision of the ELV Directive foresees a quota for use of post-consumer plastic of 25%, of which 25% must come from closed-loop material streams. Furthermore, the Critical Raw Material Acts (CRMA) [5] defines that 25% of the CRM demand of Europe should be cover through recycling in 2030. Besides, the future ELV recycling model also takes into account the Ecodesign for Sustainable Products Regulation (ESPR) [6] which aims to improve the sustainability of products by improving their circularity, energy performance, recyclability and durability.

Based on current EU sustainability goals and regulatory drafts, the following legal targets for ELV recycling in 2045 are projected as a baseline scenario:

Expected Targets per vehicle by weight:

- Reuse & Recycling: ≥ 90%
- Reuse & Recovery (including energy recovery): ≥ 98–100%
- Maximum Landfilling: 0–2%
- Targets for plastic recycling

### 2. Additional Legal Requirements

- Mandatory removal of a wide spectrum of vehicle components before ELV shredding such as batteries, electric motors or rare-earth magnets, if material quality of parts cannot be recovered by shredding- and post-shredding technologies
- 100% Traceability and Closed-Loop Recycling of EV Batteries
  Full lifecycle tracking and material recovery for electric vehicle batteries while taking into account the avoidance of additional bureaucratic burdens.
- Mandatory closed loop quotas for specific materials such as polymers
- Mandatory Recovery of Critical Raw Materials and Polymers
  Legal obligations to extract valuable elements such as lithium, cobalt, and rare earth metals and to recycle a certain percentage of automotive polymers

- More stringent and comprehensive Extended Producer Requirements (EPR) [7] Producers will be fully responsible for the vehicles from design to end-of-life including financing the entire ELV management chain.
- Digital Product, Battery and Material Passports
  Every vehicle (or on type level) and selected components such as traction battery will require a digital passport containing material, repair, and recycling data.
- Remanufacturing will be partially made legally binding and incentivized
  Dismantled vehicle components must be evaluated for reuse, remanufacturing or recycling. If deemed suitable they must be made available for reuse or remanufacturing.
- Eco-Design Regulations for Producers
  Manufacturers will be required to design vehicles for easy disassembly, modularity, and material separation.
- Landfill Bans for Recyclable Fractions
  All recyclable or energy-recoverable materials will be prohibited from landfilling.
- Greenhouse Gases / $CO_2$ Impact Reporting
  Mandatory carbon footprint tracking per recycled vehicle as part of the official recycling performance data.
- Net zero targets will drive much higher closed-loop ELV recycling quotas than today (scenario baseline: > 50% of vehicle weight)
- Equipment manufacturers will need to design products to foster repair, remanufacture and ultimately recycling.

## 3.2 Future ELV Recycling Process

### 1. ELV Collection at Collection Points

- Automated intake with full Vehicle Identification Number (VIN).
- Digital twin checked or created for each ELV if not available.
- Automatic Vehicle Deregistration
- Preparation for Transport to Recycling Hub

### 2. ELV Transport to Recycling Hub (ATF) and Preparation

- Shipment of ELVs to (de-) centralized, large (regional or nationwide) recycling hubs.
- ELV registration and initial condition detection and value assessment.
- Short-term storage in central ELV storage.

## 3. Robotic Pre-Treatment (Depollution)

- Fully robotic fluid extraction.
- Automated removal of hazardous components (e.g., lead-acid batteries, airbags) to ensure safety and compliance with environmental regulations.

## 4. Automated Dismantling

- Use of digital twin, life cycle data, visual/optical obtained data and other information to identify the best vehicle specific R-Strategy on component and material level.
- Removal of easily accessible components that will be put into existing circular economy value chains or circuits (e.g. tires, …)
- Dedicated removal and sorting of high-voltage (HV) batteries from BEVs/HEVs
- Real-time AI-driven material and component classification
- Use of industrial and humanoid robots for low cost and safe dismantling
- Robots disassemble a wide range of components which could include:
  - ➢ E-machine, electronics, wiring harnesses, composite parts, polymer modules, glass, seats, dashboards.
- Dismantled components and parts are either transferred to remanufacturing facilities or to specialized material recycling facilities.
- The ATF issues the Certificate of Destruction (CoD)


Figure: Automated dismantling (generated by AI)

## 5. Battery Recycling Stream

- HV batteries from BEVs/HEVs processed in parallel at advanced battery recycling plants (either on-site or separate location).
- Recovery of critical raw materials: lithium, nickel, cobalt, manganese, copper, aluminum.
- Closed-loop reintegration of battery materials into new cell production.

## 6. ELV Shredding at a Specialized Facility

- ELVs sent to high-volume, standardized shredding facilities for ELVs only.
- Large scale ELV shredding

## 7. High-End Post-Shredder Sorting

- Advanced sorting technologies: e.g. magnetic, eddy current, Middle-Infrared (MIR), XRF, XRT, LIBS, electrostatic, optical AI-augmented sorting.
- High-purity separation of metals, plastics, and composite fractions.
- Inline-material analysis for specific documentation of material composition

## 8. Closed-Loop Automotive Material Recovery and Refinement

- Refinement of materials in recycling mechanical recycling with melt filtration and vacuum degassing, to enhance properties or to remove impurities, alternatively chemical recycling
- New additivation and compounding to meet automotive-grade standards.
- Advanced processing of metals to reduce impurities
- Direct reintegration into OEM supply chains.
- Supports circular economy within the automotive sector.

**General Enabling Across All Process Steps:**

## 9. Digital Compliance and Traceability

- Full life cycle tracking of materials.
- Environmental and social life-cycle analysis across all process steps
- Blockchain- and data space enabled regulatory reporting.
- Enables transparent verification of recycling and recovery rates.

# 10. Minimal Residual Waste, Water Usage and Green Energy for Operations

- Waste Minimization by maximizing revalorization through Reuse, remanufacture and Recycling
- Water Circularity and Cleanliness
- 100% Use of Green Energy On-Site: All operations are powered exclusively by renewable or carbon neutral energy sources.
- Valorisation of Non-Recoverable Fractions: Non-recyclable materials are directed to other existing value chains for valorisation or directed to energy recovery processes.

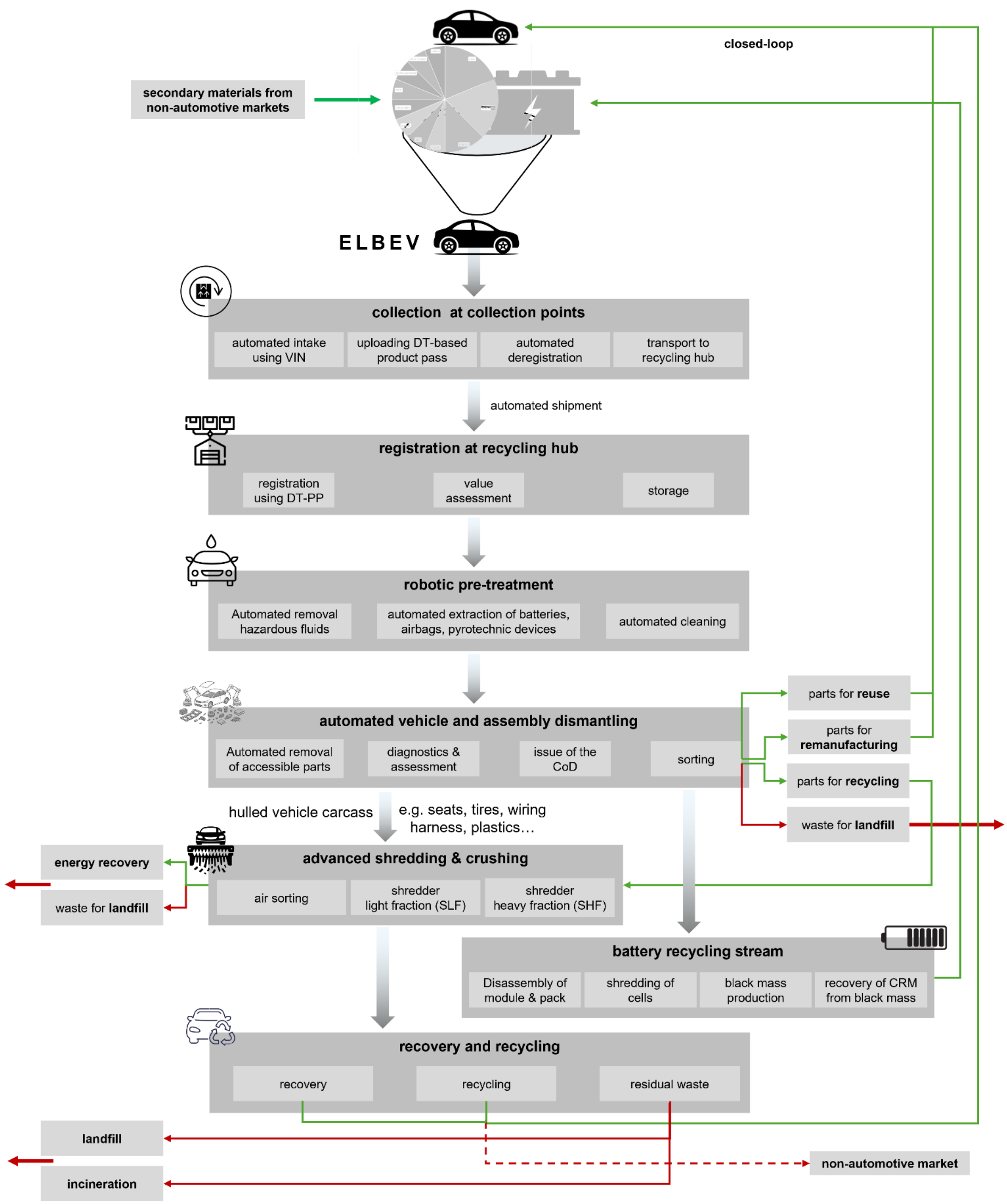


Figure: Flow Chart of the future ELBEV Recycling Process

# 4 Comparison between Status Quo and Future Model

Table: Key Differences Between Status Quo and Future Model

| Aspect | Current Process | Future Industrial Model |
|---|---|---|
| Depollution | Manual | Fully Robotic |
| HV Battery Handling | Manual, Separate Logistics | Automated, Integrated Battery Recycling |
| Dismantling Scope | Limited | Comprehensive, Automated |
| Sorting Technology | Basic | Advanced, AI-Augmented |
| Material Recovery Quality | Mixed Grades, Open-Loop | Automotive-Grade, Closed-Loop |
| Battery Recycling | Fragmented, External Facilities | Integrated, Closed-Loop with OEM Supply |
| Process Scale | Local ATFs | Large, (de-)centralized (regional or nation-wide) Recycling Hubs |
| Material Traceability | Limited | Full Digital Tracking |
| Regulatory Reporting | Batch-Based | Real-Time, Blockchain-Enabled |
| Residual Waste | Significant | Minimal |
| Compliance Model | Paper-Based | Fully Digital, Automated |

Table: Key Elements at a glance

| Element | Current Process | Future Industrial Model |
|---|---|---|
| Vehicle Intake | Manual at ATF | Automated, Digital Twin |
| Depollution | Manual | Robotic |
| HV Battery Removal | Manual | Automated, Integrated |
| Dismantling | Limited, Manual | Automated, Comprehensive |
| Shredding | Local Facilities | Specialized, High-Volume Hubs |
| Post-Shredder Sorting | Basic Magnetic/Eddy Current | AI-Driven, Multi-Sensor |
| Material Recovery Quality | Mixed Grades, Open-Loop | Automotive-Grade, Closed-Loop |
| Battery Recycling Integration | Fragmented | Closed-Loop, Direct to Battery Manufacturer |
| Traceability | Limited | Full Digital, Blockchain-Enabled |
| Residual Waste | High | Minimal |
| Regulatory Reporting | Paper-Based | Real-Time, Automated |

# 5 Conceptual Vision: A Future Automotive ELV Recycling Scenario (2045+)

## 5.1 Introduction

The Flagship "Recycling Factory of the Future" must be conceived as a cornerstone of an industrial, EU-scale circular economy for vehicles. Rather than treating end-of-life vehicles (ELVs) as waste, the facility operates as a high-precision "urban mine" and secondary raw material refinery, closing material loops for metals, polymers, and critical raw materials (CRMs) at a scale of 100,000 vehicles per year.

Anchored in the upcoming EU End-of-Life Vehicles Regulation (ELV-R), the CRM Act and the Battery Regulation [8], the plant is designed to deliver true "car-to-car" circularity: secondary materials match primary quality and can directly re-enter new vehicle production.

From a circular economy standpoint, four features are decisive:

1. **High-purity, closed-loop material flows**
    - Steel is processed to <0.1% copper contamination, allowing its use in premium automotive flat steel instead of downcycling to construction rebar.
    - Aluminum streams are separated (wrought vs. cast) to maintain ductility and formability for new body panels.
    - Polymers (PP, ABS, PE) are sorted to >99% purity with VOC and odor control (VDA 270), enabling compliance with the proposed "25% recycled plastics / 20% closed-loop from ELVs" mandate.

    The facility thereby industrializes circularity targets that would otherwise remain largely theoretical for OEMs.

2. **Recovery of critical raw materials and strategic autonomy**
    - From 100,000 ELVs, the plant recovers ~600 t Li, 2,720 t Ni, 480 t Co, 78 t REEs (incl. ~57 t Nd, 10 t Dy) and ~4,200 t graphite per year, primarily from HV batteries and permanent magnet e-motors.
    - These flows directly support CRM Act objectives that at least 25% of strategic raw material demand be met by domestic recycling by 2030 and reduce dependence on geographically concentrated and geopolitically sensitive primary supply chains.
    - High-efficiency PGM recovery (>95% Pt/Pd) from catalytic converters adds a robust, high-liquidity circular stream from ICE vehicles.

3. **Design-compatible dismantling and data-driven circularity**
    - A hybrid automation system with 20 robotic cells, AI-vision, and Digital Product Passport (DPP) integration enables non-destructive dismantling of batteries, motors, ECUs and wiring harnesses.

- This “design-for-recycling compatible” setup shortens cycle times, raises reuse/remanufacturing rates to ~25% of vehicle mass, and preserves product and material value that would be lost in shredder-first systems.
- The plant is “DPP-ready”: where DPP is present, circularity is highly efficient; where legacy vehicles lack DPPs, AI-driven diagnostics mitigate the penalty, ensuring that the system remains resilient during the transition phase.

4. **Climate impact and systemic circularity leverage**
   - By replacing primary materials with high-quality recycled steel, aluminum, copper, plastics and battery metals, the facility avoids about 513,500 $tCO_{2,eq}$ per year, based on conservative LCA factors.
   - While carbon monetization is excluded from the core business case for prudence, the carbon benefit underscores the role of ELV recycling as climate infrastructure and a key enabler for low-carbon vehicles beyond tailpipe emissions.
   - Sensitivity analysis shows that under realistic carbon pricing, circular material flows become an even stronger economic driver, reinforcing the alignment between climate, resource security, and profitability.

In combination, these elements turn the factory into a **circularity engine for the automotive sector**: it operationalizes upcoming regulatory targets, secures secondary raw material supply, and provides OEMs with a scalable route to meet recycled-content and closed-loop obligations without compromising material performance or safety.

Table: Key Circular Economy Results of a Flagship “Recycling Factory of the Future”

| **Dimension** | **Circular Economy Outcome** |
|---|---|
| Annual throughput | 100,000 ELVs/year → 161,800 t/year total vehicle mass |
| Fleet mix | 60% BEV / 40% ICE → integrates both future (BEV) and legacy (ICE) circular streams |
| Steel circularity | 79,200 t/year steel/iron with <0.1% Cu → suitable for car-to-car flat steel applications |
| Aluminium circularity | 24,800 t/year aluminum with alloy-specific sorting (wrought vs. cast) |
| Polymer circularity | 23,500 t/year plastics with >99% purity and VOC/odor control → enables 20% closed-loop ELV plastics mandate |
| CRM recovery (batteries & e-motors) | 600 t Li; 2,720 t Ni; 480 t Co; 78 t REEs (incl. ~57 t Nd, 10 t Dy); 4,200 t graphite/year |
| PGMs from ICE ELVs | >95% recovery of Pt and Pd from catalytic converters |
| Battery regulation compliance | Designed to meet Li 50→80% and Co/Cu/Ni 90→95% recovery efficiency (2027→2031) |

| Dimension | Circular Economy Outcome |
|---|---|
| Remanufacturing / reuse rate | 25% of vehicle mass (≈€1,500/vehicle value) → extends product lifetimes, avoids new production |
| Downstream material recycling share | Remaining 75% mass goes into high-purity scrap loops (metals, polymers) |
| DPP integration | Assumes full DPP coverage in base case; legacy fleet without DPP treated in sensitivity |
| Carbon impact | ~513,500 $tCO_2e$/year avoided via substitution of primary materials |
| Role in EU CRM & ELV policy | Supports CRM Act 15% recycling benchmark; operationalizes ELV-R recycled-content and closed-loop targets |
| Systemic function in auto ecosystem | Acts as a strategic secondary raw material hub and compliance platform for OEM circularity strategies |

## 5.2 Business Perspective

The "Recycling Factory of the Future" is conceived as a high-yield, large-scale ELV recycling hub that turns upcoming EU regulatory obligations into a bankable industrial business. At a throughput of 100,000 vehicles per year (60% BEV, 40% ICE scenario), it achieves an EBITDA of €188.1 million and an EBIT of €153.1 million on annual revenues of around €279 million. With a CAPEX of €350 million, this translates into a 43.7% ROI (EBIT/CAPEX), a 38.2% IRR, an EBITDA margin of 67.5%, an EBIT margin of 54.9%, a payback period of 1.9 years and a DSCR of 10.3x, clearly above typical thresholds for green project finance. These economics are supported by robust assumptions, conservative treatment of upside factors such as carbon credits, and a ramp-up profile that reaches full profitability from year three onward.

The value creation rests on four main pillars. First, the business model is anchored in Extended Producer Responsibility under the future ELV Regulation: by acting as a compliance partner to OEMs, the plant assumes a baseline Vehicle Acquisition Cost of €0, enabled by Article 8a EPR obligations [7]. This "zero-cost feedstock" is stress-tested up to €500 per vehicle and the business case remains highly profitable. Second, the facility monetizes premium material quality. Automated depollution and dismantling (including Annex VII components) combined with advanced LIBS/XRF/NIR sorting deliver low-copper steel (<0.1% Cu), high-grade aluminum (<0.2% Fe) and >99% pure polymers (PP, ABS, PE) that qualify for "car-to-car" applications and the 20% closed-loop plastics mandate. These fractions command 15–50% price premiums over standard scrap and generate about €128.6 million per year. Third, AI-based non-destructive dismantling enables high-value remanufacturing: a conservative 25% mass commercialization of components (e.g. HV batteries for second life, e-motors, electronics, engines, gearboxes, catalytic converters) yields approximately €1,500 per vehicle or €150 million annually, making remanufacturing the dominant revenue stream with 54% share and 2–5x scrap value uplift. Fourth, high automation and a "humanoid-ready" design cut operating costs: only about 250 employees are required, reducing OPEX to €90.5 million per year (€905/vehicle), roughly half the cost of manual facilities, with further upside from future AI and humanoid robotics. At the same time, the facility avoids approximately 513,500 tonnes of $CO_2$ emissions per year by substituting primary materials with secondary ones. While this "green alpha" is excluded from the base case due to current ETS/ETS-II uncertainties, integrating a carbon price of €100/t$CO_2$ would raise the ROI above 58%. Sensitivity analyses show that the business remains well above typical WACC even under adverse scenarios for feedstock cost, throughput, reuse yield, or DPP coverage, while shocks such as material price spikes or the introduction of robust carbon pricing dramatically increase profitability.

Table: Business perspective of a Flagship "Recycling Factory of the Future"

| Metric | Value | Technical/Strategic Basis |
|---|---|---|
| Annual Revenue | €278.6 Million | Driven by "Tier 0" material purity and remanufactured parts. |
| CAPEX | €350.1 Million | 20 robotic cells, AI-vision infra, and High-Precision Sorting |
| OPEX | €90.5 Million p.a. | Low labor costs due to AI-automation (250 staff) and €0 input cost. |
| Annual EBITDA | €188.1 Million p.a. | Reflects a market-leading **67.5% margin**. |
| Annual EBIT | €153.1 Million p.a. | Reflects a **fast track to profitability**. |
| ROI (EBIT/CAPEX) | 43.7% | Purely technical/material-driven; 0% Carbon Credit reliance. |
| Payback Period | 1.9 Years | Rapid deleveraging due to high industrial throughput (100k units). |
| DSCR | 10.3x | Exceptional resilience for green project financing. |

## 5.3 R&I Needs

The following Research and Innovation (R&I) needs for an EU Flagship project "Recycling Factory of the Future" are based on the ERTRAC Roadmap for Circularity and Competitiveness [9]. The project will focus solely on the process steps highlighted in yellow.

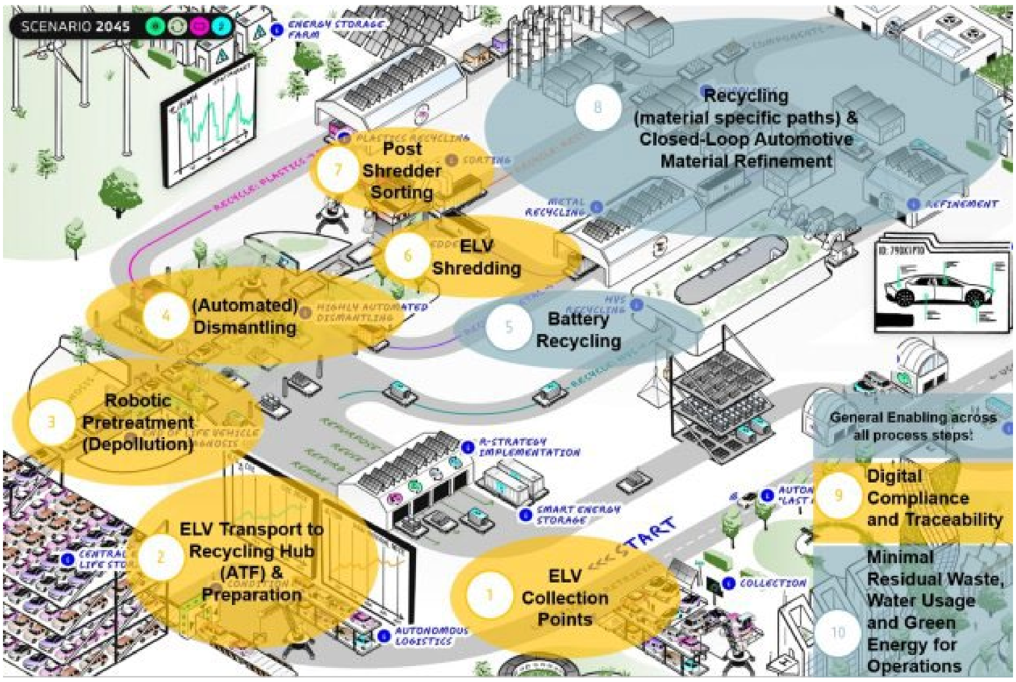


Figure: Future ELV Treatment Scenario (example)

In some cases, these needs have been expanded or described in greater detail, others have been added for further discussions.

It is assumed that all facilities operate using green/renewable energy to ensure zero-emission processes, along with advanced water purification systems. Therefore, specific research needs related to energy and water management are not listed separately.

In line with the current discussion within the WG C&C team to exclude traction battery recycling - as it is considered a substantial, standalone topic - it is proposed that the future flagship project on recycling facilities should instead focus on the automated dismantling of high-voltage batteries from End-of-Life Vehicles (ELVs). Following dismantling, the batteries would be automatically transported to a specialized recycling facility. This facility could be either co-located within the same industrial site - if a sufficient volume ensures economically viable operations - or located elsewhere at a site dedicated to battery recycling.

This logic can also be applied to other material classes, too: if on-site recycling and refinement are financially viable, these processes can be performed locally, significantly reducing logistics and handling costs. However, achieving closed-loop material characteristics often requires complex and cost-intensive recycling and refinement steps (e.g., chemical recycling or the removal of zinc coatings from steel).

Therefore, the baseline assumption for the identification of R&I needs is that such material recycling and refinement processes fall outside the scope of the recycling factory project. As a result, the project will focus on automated preparation / depollution, dismantling, shredding, and advanced sorting processes.

As remanufacturing is typically an OEM- or even brand-specific operation, R&I needs related to the reuse or remanufacturing of components are not included in the scope of the proposed flagship project.

| Element | R&I Needs |
|---|---|
| ① **ELV Collection at Collection Points** | - **Digital Tracking and Tracing Technologies of Vehicles**: Research is needed to enable full lifecycle traceability of vehicles and their components, including reusable parts and recyclable materials. Certified data exchange and circular KPI integration will help reduce the share of ELVs with unknown whereabouts and support legal compliance in dismantling and recycling.<br>- **Level 4/5 Autonomous Driving Capabilities**: Deploying Level 4/5 autonomous driving for ELV transport to collection points requires further research in safe navigation, geofencing, and mixed-traffic integration. Scalable deployment models and regulatory frameworks must also be addressed.<br>- **Collection Point Design**: New collection point designs should accommodate automated vehicle intake, pre-sorting, and secure temporary storage. Research should explore modular infrastructure, user-friendly interfaces, and real-time digital connectivity with downstream systems.<br>- **Autonomous Logistics**: Autonomous logistics between local collection points and central hubs will increase efficiency and reduce labor intensity. Key research areas include route planning, fleet coordination, and adaptive scheduling systems. |

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| ② <br><br> **ELV Transport to Recycling Hub (ATF) and Preparation** | - **Digital Product Passports Battery and Material Passports**: Developing more detailed, standardized and interoperable Digital Product Passports, Battery and Material Passport solutions is a critical research area. These passports should capture key data such as component health, material composition, recyclability potential, and repair history to improve tracking and facilitate the reuse and recycling of automotive components. On this basis automated data analysis of DPP data and decision support systems should be developed to optimize product and process design parameters regarding their circularity (easy to dismantle, easy to recycle).<br>- **Design of Condition Detection Facility**: Developing condition detection facilities with integrated automation is essential to optimize ELV intake and assessment. Research should focus on scalable systems that enable real-time scanning, valuation, and classification of incoming vehicles to guide further processing.<br>- **Autonomous Cranes in Facilities**: Autonomous cranes that register ELV arrivals and handle vehicles securely into designated storage areas are a critical enabler for hands-free logistics. Research should advance AI-based on-site navigation and load-handling to ensure efficiency and safety.<br>- **Autonomous Dismantling Platform Coordination**: Autonomous dismantling platforms where ELVs are dismantled that interact with crane systems to signal designated placement areas will improve throughput and spatial planning. Interoperable communication protocols and real-time system coordination remain key research areas.<br>- **Real-Time Market Price Integration**: Integrating real-time market data for components and materials is crucial for selecting optimal R-strategies. Research should address secure, up-to-date price feeds and their integration into decision-making systems.<br>- **Autonomous Logistics**: Fully autonomous transport between processing stations and storage sites is a long-term goal. Key research needs include reliable pathfinding, obstacle avoidance, and integration with facility-wide logistics systems.<br>- **Buffer Storage Design with Autonomous Transport**: Synchronizing buffer storage with autonomous movement requires modular storage design and smart inventory systems. Research should focus on spatial optimization and coordination algorithms.<br>- **AI-Assisted ELV Prioritization from Buffer Storage**: Database cross-checking to identify and prioritize high-value ELVs will increase operational efficiency. Research is needed on AI-driven valuation models and responsive retrieval logistics.<br>- **Buffer Storage, Packing, and Transport for Valuable Parts:** Setting up secure buffer zones for valuable parts, with optimized packing and outbound logistics, is essential for maximizing recovered value. Research should target modular packaging and material handling systems. |

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| ③<br><br>**Robotic Pre-treatment (De-pollution)** | - **3D Scan & Screening Technologies**: Advanced 3D scanning and value screening technologies are needed to assess vehicles at entry points, enabling dynamic decisions on part recovery or full destruction. Research should explore high-speed scanning, value algorithms, and market linkage.<br>- **Improved Image Recognition and Robotic Dismantling**: Enhanced image recognition and robotic dismantling technologies will support precise component recovery. Research is required on adaptable recognition models and robotic manipulation for varied ELV structures.<br>- **(Semi-)Automated Dismantling Before Shredding**: Develop methodologies for efficiently dismantling vehicles before shredding to minimize contamination from tramp elements. This could involve creating specialized tools and training for workers to disassemble vehicles safely and efficiently.<br>- **Secure Disposal and Documentation of Hazardous Materials**: Safe and traceable disposal of hazardous materials requires AI-supported systems and robotic assistance. Research should address risk-based decision-making models and documentation processes for legal and environmental compliance<br>- **Part and Material Tracking Including Ownership and Pricing**: End-to-end tracking of parts and materials, including real-time ownership and price data, is critical for traceability and value optimization. Research should focus on blockchain or equivalent secure tracking frameworks.<br>- **DPP Access and Status Change Capabilities**: Reliable access to Digital Product Passports (DPPs) across borders and platforms is essential. Research should focus on secure data exchange, identity verification, and interoperability despite company-specific data protection policies. |
| ④<br><br>**(Automated) Dismantling** | - **Autonomous Material Transport with AI-Supported Tracking**: Material streams must be autonomously transported between dismantling, recycling, and sorting stations. Research should advance AI-driven systems for real-time tracking, value assessment, and dynamic routing of materials.<br>- **Design of Safe Disposal Locations with Full Tracking**: Research is needed to develop disposal sites with real-time documentation of hazardous materials, their classifications, and decomposition timelines. Smart tracking and secure data storage must be integrated from the outset.<br>- **Disassembly Technologies**: Develop semi-automated or automated disassembly technologies based on available automation systems such as production robots.<br>- **Humanoid Robotics Disassembly**: Besides the application of conventional industrial robots for dismantling tasks future humanoid robotics offer great potential for highly flexible dismantling tasks in complex and unpredictable ELV environments. Research is needed to develop dexterous manipulation, adaptive learning, and safe human-robot collaboration for use in dismantling lines.<br>- **Diagnostics and Assessment of assemblies and parts:** AI-based state-of-health assessment and decision support to route parts into reuse, remanufacturing or material recycling |

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| | - **Parts and Material Classification Methods**: Automated classification methods are essential to optimize dismantling workflows and recovery quality. Research should develop robust sorting algorithms based on material type, condition, and reuse potential. |
| ⑥<br><br>**ELV Shredding at Specialized Facility** | - **Dust Collection and Filtering**: Effective dust collection and filtering systems are critical to protect worker health and environmental quality during shredding. Research should focus on high-efficiency, scalable capture technologies, automated monitoring, and filter material innovations.<br>- **Noise Dampening**: Shredding operations generate significant noise pollution, requiring advanced acoustic mitigation. Research should explore new dampening materials, enclosure designs, and real-time adaptive noise control systems.<br>- **Energy Efficiency**: Improving the energy performance of shredding machinery is essential for both cost and emissions reduction. Research should focus on energy recovery systems, optimized motor control, and lightweight rotor designs.<br>- **Digitalization and Monitoring**: Digital monitoring of shredding operations enables transparency, quality assurance, and traceability. Research is needed into sensor networks, data integration platforms, and anomaly detection for operational insights.<br>- **Predictive Maintenance**: Implementing predictive maintenance through sensor data and machine learning can reduce downtime and increase equipment lifespan. Research should target robust degradation models and condition-based alert systems.<br>- **Modular Design**: Developing modular shredding facility components allows flexible upgrades, easier repairs, and system scaling. Research should address standardized interface design and rapid replacement technologies.<br>- **Emission Capture and Treatment**: Shredding processes may release volatile organic compounds or other emissions. Research should explore compact emission capture units and integrated treatment systems for regulatory compliance.<br>- **Digital Material Flow Mapping**: Digital mapping of material flows through shredding processes can improve recovery strategy planning. Research should target real-time data capture, visualization tools, and integration with DPP systems.<br>- **Resilient Shredder Design for New Vehicle Materials and optimized Post-Shredder Sorting**: As vehicle designs evolve with more composites and lightweight materials, shredders must adapt. Research is needed on blade designs, wear resistance and material-specific processing parameters. |

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| ⑦<br><br>**High-End Post-Shredder Sorting** | - **Advanced Post-Shredder Sorting Technologies**: Research is needed to advance sensor-based and AI-augmented sorting systems, including magnetic, eddy current, Near-/Mid-Infrared Hyperspectral Imaging, LIBS, electrostatic, and X-ray technologies. These systems are key to improving material purity and enabling high-quality recycling outputs.<br>- **High-Efficiency Scrap Metal Sorting Processes:** Invest in advanced sorting technologies, such as AI-driven optical sorting and magnetic separation, to improve the quality of recycled metals and reduce costs. Research should focus on optimizing these technologies for different types of metals and alloys.<br>- **Investments into Pre- and Post-Shredder Technologies**: Future sorting efficiency relies on upstream and downstream technology integration. Research should support the evaluation and development of systems that prepare materials for optimized post-shredder recovery.<br>- **Investments into Humanoid Robots**: Humanoid robotics can perform adaptive sorting and quality control in complex material streams. Research should explore dexterity, safe interaction in dynamic environments, and learning-based material identification.<br>- **Investments into Sell & Buy Platforms (Matchmaking)**: Digital platforms that match recovered materials with potential buyers will streamline circular value chains. Research should focus on quality certification, pricing transparency, and real-time inventory linking.<br>- **Logistics and Preparation for Tracking and Tracing**: Effective post-shredder sorting requires traceable material flow from source to market. Research is needed on digital tagging, automated logistics coordination, and secure tracking frameworks integrated with DPP systems.<br>- **Improvement of recycled feedstock sorting and refining process for polymers**: Research on developing technologies that allow to increase recycled feedstock purity and quality, ensuring that the majority of recycled materials can be valorised through mechanical recycling with the highest ability to maintain polymer quality.<br>- **AI-Assisted Dismantling and Sorting Technologies**: AI-enhanced systems are vital for automation and accuracy in sorting and recycling. Research should focus on data-driven classification, robotic execution, and feedback loops for continuous improvement.<br>- **High-Efficiency Scrap Metal Sorting Processes**: New methods for separating ferrous and non-ferrous metals with minimal contamination are needed. Research should investigate fast, accurate, and scalable technologies for clean metal recovery.<br>- **Sorting Technologies for Composite and Multi-Layered Materials**: As vehicles increasingly use advanced composite materials, research is needed on separating and recovering these materials effectively from mixed shredder output. |

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| | - **Real-Time Material Valuation Systems**: Integration of market data into sorting systems can guide dynamic decisions during material separation. Research should explore value estimation models and decision-support integration with sorting equipment.<br>- **Post-Sorting Quality Assurance and Certification**: Establishing digital quality assurance systems for sorted fractions supports downstream reuse. Research should address automated verification methods and blockchain or traceable certification protocols.<br>- Digital twin of the sorting processes with the aim, for example, of analysing the chemical composition in the sorting process on a batch basis and then passing this information on to the downstream process chains (material supplier). |
| ⑨<br>**Digital Compliance and Traceability** | - **Standardisation of Data Formats and Protocols**: Research is needed to establish universal standards for data formats, digital product passports, and tracking systems. Standardisation will improve interoperability across different platforms and stakeholders, facilitating smoother data exchange and automating the tracking of materials and components throughout their lifecycle.<br>- **Blockchain, Data spaces and Distributed Ledger Technologies**: Research into improving the scalability, security, and efficiency of blockchain, data spaces and distributed ledger technologies for tracking automotive parts and materials is essential. These technologies can provide tamper-proof records of a part's lifecycle, enabling greater transparency and accountability in the circular economy.<br>- **Digital Tracking and Tracing Technologies of Vehicles:** Research is needed to track and trace vehicles until they reach end-of-life status regardless of their age and location as well as the reusable components and recyclable materials including the certified data exchange of relevant circular KPIs. This is important to bring unknown-whereabouts in organization and legally compliant dismantling and recycling system.<br>- **Integration of Circular Economy into Digital Supply Chain Management:** Research should focus on the integration of circular economy principles into digital supply chain systems while complying with GDPR. This involves developing platforms that enable real-time tracking, forecasting, and decision making to optimise the flow of materials and components while minimizing waste.<br>- **Integration of Digital Product Passports and Circular Economy:** Digital Product Passports (DPPs) and Environmental Product Declarations (EPDs) are emerging as critical tools for delivering infrastructure more sustainably. Methodologies are needed for integrating these new processes with existing infrastructure assets. |

## 5.4 Future Logistics Model – The Backbone of Cost-Efficient ELV Recycling


Figure: Automated Reverse Logistics (generated by AI)

In the future ELV recycling ecosystem, logistics will be a critical enabler of both cost efficiency and environmental performance. The consolidation of recycling operations into large, high-volume hubs increases transport distances compared to the current decentralized system.

Without significant innovation in logistics, these additional distances would result in higher costs and additional carbon emissions. To address this, integration of autonomous transport systems is essential. These systems include:

- Autonomous Electric Trucks: Enabling low-cost, low-emission (long-haul) transport between vehicle collection centers, recycling hubs and subsequent specialized facilities to recycle batteries or other materials and remanufacture components.
- Rail-Based Autonomous Container Systems: Supporting efficient, high-volume material flows across Europe, reducing road congestion and emissions.
- Automated Guided Vehicles (AGVs): Facilitating on-site transfers within recycling hubs and battery processing facilities.

<u>Advantages of Autonomous Logistics:</u>

- Substantial labor cost savings.
- 24/7 operation without driver limitations.
- Enhanced energy efficiency through optimized routing and platooning.

Detailed Logistics Process:

- Collection and Further Transport to Recycling Hubs
  - Vehicles drive itself autonomously (L4/L5) to collection points or if they are not able to are being driven or brought there.
- Transport to regional collection centers is performed autonomously by autonomous truck and/or trains.
- Intra-Hub Transport: Vehicle carcasses are transported to robotic dismantling and high-end shredding hubs using autonomous trucks or rail-based autonomous containers.
- Post-Sorting Material Flows:
  - Recovered material fractions are autonomously transported to reprocessing centers and OEM production sites.
- Reintegration:
  - Automotive grade recycled materials are digitally tracked and efficiently reintegrated into OEM manufacturing processes.

By embedding autonomous transport throughout all stages, the future ELV recycling model achieves competitive transport costs and maximizes sustainability, supporting the circular economy ambitions of the European automotive industry.

# 6 Conclusions and Recommendations

EU's current ELV system, although achieving today's mass-based targets, is not fit for purpose for a net-zero, resource-sovereign and highly electrified automotive sector. Manual depollution and dismantling, limited digitalisation, predominantly open-loop material flows and significant residual waste mean that valuable materials – especially plastics and critical raw materials – are still lost, and that ELVs are not yet a strong backbone of the circular automotive economy. Looking towards 2045+, the envisaged model replaces this fragmented, labour-intensive structure with large, industrialised, highly automated and data-driven recycling hubs, tightly integrated into OEM supply chains. Robotics, AI-supported condition and material analysis, advanced shredding and post-shredder sorting, together with digital twins, product and battery passports and blockchain-enabled compliance, enable high-purity, closed-loop material cycles with near-zero landfilling. In this future setting, ELV recycling is no longer a waste management activity at the end of the chain but a strategically important industrial operation that reduces dependency on virgin raw materials, supports climate targets and underpins European industrial competitiveness. However, this transformation requires substantial research, innovation and system-level coordination. The flagship "Recycling Factory of the Future" project is positioned as a central instrument to close the gap between today's state and this ambitious 2045+ scenario by focusing on automated depollution, dismantling, shredding and high-end sorting, with traction battery material recycling and OEM-specific remanufacturing treated as tightly linked but separate domains.

On this basis, current mass-based targets must evolve towards ambitious, material- and quality-oriented targets, including closed-loop requirements for critical materials and polymers, mandatory recovery of key elements (e.g. CRMs, engineering polymers), landfill bans for recyclable fractions and mandatory digital product, battery and material passports. Automotive industry should broaden and deepen their strategy towards circular economy for achieving specified closed-loop shares in their own material supply. At the same time, regulation must safeguard against unnecessary administrative burden by making digital traceability and reporting as automated and interoperable as possible.

Industry and research actors should jointly develop and demonstrate fully robotic depollution and automated dismantling, including humanoid or collaborative robots capable of handling heterogeneous vehicle designs safely and cost-effectively. Investments should be made in AI-based state-of-health assessment and decision support to route parts into reuse, remanufacturing or material recycling, and in high-precision post-shredder sorting technologies (e.g. MIR, XRF, XRT, LIBS, electrostatic and optical systems) combined with inline material analytics to achieve automotive-grade secondary raw materials at scale. Logistics must be recognised and treated as a strategic enabler: the move toward fewer, larger hubs must be supported by autonomous, low-emission transport solutions (autonomous electric trucks, rail-based container systems, AGVs) to keep costs low and carbon footprints minimal. Standardisation efforts are needed for data models, digital passports, dismantling interfaces and material specifications so that different OEMs, recyclers and logistics providers can interact seamlessly. Finally, public funding at EU and national level should prioritise large, integrated pilots of such “factories of the future”, including real-life operation with significant ELV volumes, to validate business models, refine regulatory frameworks and accelerate industrial uptake.

If these recommendations are implemented in a coordinated way, the future ELV system can evolve into a cornerstone of the European circular economy, providing secure, high-quality secondary materials, reducing environmental impacts across the vehicle life cycle and reinforcing Europe’s technological and industrial sovereignty.

Overall, the plant operates as a high-volume “resource refinery” that monetizes regulatory change, secures critical materials, and delivers exceptional, resilient returns, making it a compelling cornerstone asset for industrial-scale circular economy infrastructure in Europe. Such a facility is a high-volume industrial engine designed to monetize the transition to a circular economy. It offers a rare combination of regulatory necessity, proven technical scale, and exceptional financial robustness.

# 7 Annex

## 7.1 List of Abbreviations

| Abbreviation | Meaning |
|---|---|
| ABS | Acrylnitril-Butadien-Styrol |
| AGV | Automated Guided Vehicle |
| AI | Artificial Intelligence |
| ASR | Automotive Shredder Residue |
| ATF | Authorised Treatment Facility |
| BEV | Battery Electric Vehicle |
| CAPEX | Capital Expenditures |
| CoD | Certificate of Destruction |
| CRM | Critical Raw Material |
| DSCR | Debt-Service-Coverage-Ratio |
| DPP | Digital Product Passport |
| EBIT | Earnings before Interest and Taxes |
| EC | European Commission |
| ECU | Electronic Control Unit |
| ELBEV | End-of-Life Battery Electric Vehicle |
| ELV | End-of-Life Vehicle |
| EPR | Extended Producer Responsibility |
| ERTRAC | European Road Transport Research Advisory Council |
| ETS | European Union Emissions Trading System |
| HEV | Hybrid Electric Vehicle |
| HV | High Voltage |
| ICE | Internal Combustion Engine |
| LCA | Life Cycle Assessment |
| LIBS | Laser-induced breakdown spectroscopy |
| MIR | Mid-infrared |
| OEM | Original Equipment Manufacturer |
| OPEX | Operational Expenditures |
| PE | Polyethylene |
| PGM | Platinum Group Metals |
| PP | Polypropylene |
| REE | Rare Earth Element |
| R&I | Research & Innovation |
| RoI | Return on Invest |
| SHF | Shredder Heavy Fraction |

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| SLF | Shredder Light Fraction |
| VDA | Verband der Automobilindustrie e.V. |
| VIN | Vehicle Identification Number |
| XRF | X-Ray Fluorescence |
| XRT | X-Ray Transmissive sorting |

## 7.2 References


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