Module 6

Introduction to environmental challenges and waste in the automotive industry

Simona ISTRIȚEANU

Advanced methods of waste recovery

Co-funded by the Erasmus+ Programme of the European Union

DRIVEN

Module_6

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ACRONYMS

ACEA European Automobile Manufacturers' Association

ASR Automotive Shredder Residue

ATF Authorized treatment facilities

BEV Battery electric vehicle

CCI Circular Cars Initiative

CE Circular Economy

DSM Digital Single Market

ELV End-of-life vehicle

ELT End-of-life tire

EPR Extended Producer Responsibility

EU European Union

GDPR General Data Protection Regulation

GHG Greenhouse Gases

IoT Internet of things

IPR intellectual property right

IT information technology

LCA Life-cycle assessment

OEM Original Equipment Manufacturer

PEF Product environmental footprint

REACH Registration, Evaluation, Authorisation and Restriction of Chemicals (regulation)

RFID Radio-Frequency Identification

R&D Research and Development

RSMS Restricted Substances Management Standards

SDG Sustainable Development Goal

SME Small-and medium-sized enterprise

UN United Nations

VAT value-added tax

WEEE waste electrical and electronic equipment

GLOSARY OF TERMS USED

DEFINITIONS ACCORDING WITH DIRECTIVE 2000/53/EC ON END-OF LIFE VEHICLES

For the purposes of this Directive:

1. ‘vehicle’ means any vehicle designated as category M_1 or N_1 defined in Annex IIA to Directive 70/156/EEC, and three wheel motor vehicles as defined in Directive 92/61/EEC, but excluding motor tricycles;

2. ‘end-of life vehicle’ means a vehicle which is waste within the meaning of Article 1(a) of Directive 75/442/EEC;

3. ‘producer’ means the vehicle manufacturer or the professional importer of a vehicle into a Member State;

4. ‘prevention’ means measures aiming at the reduction of the quantity and the harmfulness for the environment of end-of life vehicles, their materials and substances;

5. ‘treatment’ means any activity after the end-of life vehicle has been handed over to a facility for depollution, dismantling, shearing, shredding, recovery or preparation for disposal of the shredder wastes, and any other operation carried out for the recovery and/or disposal of the end-of life vehicle and its components;

6. ‘reuse’ means any operation by which components of end-of life vehicles are used for the same purpose for which they were conceived;

7. ‘recycling’ means the reprocessing in a production process of the waste materials for the original purpose or for other purposes but excluding energy recovery. Energy recovery means the use of combustible waste as a means to generate energy through direct incineration with or without other waste but with recovery of the heat;

8. ‘recovery’ means any of the applicable operations provided for in Annex IIB to Directive 75/442/EEC;

9. ‘disposal’ means any of the applicable operations provided for in Annex IIA to Directive 75/442/EEC;

10. ‘economic operators’ means producers, distributors, collectors, motor vehicle insurance companies, dismantlers, shredders, recoverers, recyclers and other treatment operators of end-of life vehicles, including their components and materials;

‘hazardous substance’ means any substance which fulfils the criteria for any of the following hazard classes or categories set out in Annex I of Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures (1);

(a) hazard classes 2.1 to 2.4, 2.6 and 2.7, 2.8 types A and B, 2.9, 2.10, 2.12, 2.13 categories 1 and 2, 2.14 categories 1 and 2, 2.15 types A to F;

(b) hazard classes 3.1 to 3.6, 3.7 adverse effects on sexual function and fertility or on development, 3.8 effects other than narcotic effects, 3.9 and 3.10;

(c) hazard class 4.1;

(d) hazard class 5.1;

12. ‘shredder’ means any device used for tearing into pieces or fragmenting end-of life vehicles, including for the purpose of obtaining directly reusable metal scrap;

13. ‘dismantling information’ means all information required for the correct and environmentally sound treatment of end-of life vehicles. It shall be made available to authorised treatment facilities by vehicle manufacturers and component producers in the form of manuals or by means of electronic media (e.g. CD-ROM, on-line services).

DEFINITIONS ACCORDING WITH DIRECTIVE 2008/98/EC

For the purposes of Directive 2008/98/EC, the following definitions shall apply:

1. ‘waste’ means any substance or object which the holder discards or intends or is required to discard;
2. ‘hazardous waste’ means waste which displays one or more of the hazardous properties listed in Annex III;
3. ‘waste oils’ means any mineral or synthetic lubrication or industrial oils which have become unfit for the use for which they were originally intended, such as used combustion engine oils and gearbox oils, lubricating oils, oils for turbines and hydraulic oils;
4. ‘bio-waste’ means biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants;
5. ‘waste producer’ means anyone whose activities produce waste (original waste producer) or anyone who carries out pre-processing, mixing or other operations resulting in a change in the nature or composition of this waste;
6. ‘waste holder’ means the waste producer or the natural or legal person who is in possession of the waste;
7. ‘dealer’ means any undertaking which acts in the role of principal to purchase and subsequently sell waste, including such dealers who do not take physical possession of the waste;
8. ‘broker’ means any undertaking arranging the recovery or disposal of waste on behalf of others, including such brokers who do not take physical possession of the waste;
9. ‘waste management’ means the collection, transport, recovery and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker;
10. ‘collection’ means the gathering of waste, including the preliminary sorting and preliminary storage of waste for the purposes of transport to a waste treatment facility;
11. ‘separate collection’ means the collection where a waste stream is kept separately by type and nature so as to facilitate a specific treatment;
12. ‘prevention’ means measures taken before a substance, material or product has become waste, that reduce:

(a) the quantity of waste, including through the re-use of products or the extension of the life span of products;
(b) the adverse impacts of the generated waste on the environment and human health; or
(c) the content of harmful substances in materials and products;
13. 're-use' means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived;
14. 'treatment' means recovery or disposal operations, including preparation prior to recovery or disposal;
15. 'recovery' means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II sets out a non-exhaustive list of recovery operations;
16. 'preparing for re-use' means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing;
17. 'recycling' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations;
18. 'regeneration of waste oils' means any recycling operation whereby base oils can be produced by refining waste oils, in particular by removing the contaminants, the oxidation products and the additives contained in such oils;
19. 'disposal' means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy. Annex I sets out a non-exhaustive list of disposal operations;
20. 'best available techniques' means best available techniques as defined in Article 2(11) of Directive 96/61/EC.

TERMS AND DEFINITIONS ACCORDING TO ISO 22628:2002

3.1 vehicle mass

m_V

complete vehicle shipping mass, as specified in ISO 1176, plus the mass of lubricants, coolant (if needed), washer fluid, fuel (tank filled to at least 90 % of the capacity specified by the manufacturer), spare wheel(s), fire extinguisher(s), standard spare parts, chocks, standard tool-kit

Note 1 to entry: Adapted from ISO 1176, “complete vehicle kerb mass”.

3.2 re-use any operation by which component parts of end-of-life vehicles are used for the same purpose for which they were conceived

3.3 recycling

reprocessing in a production process of the waste materials for the original purpose or for other purposes, excluding processing as a means of generating energy

3.4 recovery reprocessing in a production process of the waste materials for the original purpose or for other purposes, together with processing as a means of generating energy

3.5 dismantlability ability of component parts to be removed from the vehicle

3.6 reusability ability of component parts that can be diverted from an end-of-life stream to be reused

3.7 recyclability ability of component parts, materials or both that can be diverted from an end-of-life stream to be recycled

3.8 recyclability rate

R_{cyc}

percentage by mass (mass fraction in percent) of the new vehicle potentially able to be recycled, reused or both

3.9 recoverability ability of component parts, materials or both that can be diverted from an end-of-life stream to be recovered

3.10 recoverability rate

R_{cov}

percentage by mass (mass fraction in percent) of the new vehicle potentially able to be recovered, reused or both

TERMS USED IN ELT MANAGEMENT

Source: Global ELT Management – A global state of knowledge on regulation, management systems, impacts of recovery and technologies, 2019

Cement and other energy production: Recovery methods by which ELT are used as tire-derived fuel (TDF) in energy intensive industries such as cement kilns, power plants and industrial boilers. In the case of cement kilns both energy and material recovery occurs in the process.

Civil engineering and backfilling: Recovery route where ELT are recovered through civil engineering applications (water retention and infiltration basins, supporting walls, etc.) and through landfilling of mining activities (tires that are shredded and mixed in with other geological materials to reclaim sites that have been mined out for example).

Devulcanization: Chemical process by which bonds of vulcanized rubber are broken without shortening the carbon chains. Devulcanization is a recovery method for material recovery.

Devulcanized rubber: Rubber produced from the devulcanization process.

End-of-Life Tire or End-of-Life Tires (ELT): A tire that can no longer serve its original purpose on a vehicle. This excludes tires that are retreaded, reused, or exported in used cars.

End-of-life vehicle (ELV): A vehicle that can no longer serve its original purpose.

Energy recovery: Recovery category where ELT are recovered as tire-derived fuel (TDF). For the purpose of this study, it was considered that 75% of ELT used in cement kilns are recovered as energy. For ELT that are recovered through unknown means of recovery, a 50/50 split has been made between energy recovery and material recovery except for China where material recovery is favored.

Extended Producer Responsibility (EPR): In the case of ELT, the producer of tires (manufacturer or importer) is held responsible by law to organize the ELT management, with targeted volumes generally defined based on the quantities of tires put onto market.

Gate fee (or tipping fee): The price levied on the entity delivering ELT to a landfill or to a recovery or a recycling facility.

Granulation: Recovery method which involves the breaking down of ELT into smaller particles through different processes to obtain rubber granulate and powder, used in multiple applications.

Hybrid recovery route: ELT recovery routes which lead to both energy and material recovery (e.g. use of ELT in cement kilns).

Material recovery: Recovery route category where ELT are recovered as a new material. It can be used to produce tire-derived material (TDM) for instance. For the purpose of this study, it was considered that 25% of ELT used in cement kilns are recovered as material. For ELT that are recovered through unknown means of recovery, a 50/50 split has been made between energy recovery and material recovery except for China where material recovery is favored.

Off–the-road tires (OTR tires): Tires used on large vehicles that are capable of driving on unpaved roads or rough terrain. Vehicles include tractors, forklifts, cranes, bulldozers, earthmoving equipment, etc.

OICA, International Organization of Motor Vehicle Manufacturers (Organisation Internationale des Constructeurs d'Automobiles): International trade organization representing the global automotive industry.

Producer Responsibility Organization (PRO): An entity that is either set up directly by a government or by producers in the context of EPR, to organize ELT management and associated requirements such as recovery targets.

Pyrolysis: Decomposition of ELT material into oil, gas, steel and char in different proportions depending on conditions under pressure and high temperatures and usually the absence of oxygen. Carbonisation, gasification and thermolysis are related recovery methods.

Reclamation/reclaim rubber process: Conversion of vulcanized rubber waste into a state in which it can be mixed, processed, and vulcanized again. Reclamation usually involves a chemical process. It is a recovery method. This does not refer to authorized landfill or backfilling in this case.

Reclaimed rubber: Rubber produced from the reclamation process, which can be vulcanized again.

Recovery application: The use of a recovery product (see below) e.g. tire granulate in rubber-modified asphalt.

Recovery method: The process used to treat an ELT e.g. granulation.

Recovery product: The output following processing through a recovery method e.g. tire granulate.

Recovery route (RR): The value chain from the point of collection, through processing and treatment methods to products and applications reaching end markets. For the purpose of this study, retreaded, reused, landfilled or stock-piled tires are not considered as ELT recovered.

Recycling: This involves reprocessing of articles such as ELT to produce products, materials or substances. This excludes the production of tire-derived fuel (see below).

Regrooving: Consists of cutting a pattern into the tire's base rubber.

Retreading: Also known as recapping or remoulding. Process of renewal of tires for reuse by replacing the worn-out rubber belts/treads with new ones.

State of knowledge (SOK): A review and analysis of the current information available on a topic. In this context the aim is to provide an overview of the ELT management systems in place including the ELT collection rates, recovery routes, and management methods.

Steel production: Use of ELT in the form of extracted tire-derived steel for the production of new iron, or steel in electric arc furnaces, steel mills and foundries for the manufacturing of secondary steel. Use of ELT in steel production is a recovery method.

Tire-derived material (TDM): Recovery sub-category. TDM is a product made from the recycled material of ELT.

Tire-derived fuel (TDF): Recovery sub-category. TDF is ELT used as an alternative fuel to produce energy through combustion (energy recovery). TDF also refers to the fuels produced by a specific treatment of ELT (such as pyrolysis, which can produce oil and gas output products along with a TDM portion). Although the use of ELT in cement production is considered both energy and material recovery, it is included in TDF for the purpose of the report.

Tire Industry Project (TIP) members: Bridgestone Corporation, Continental AG, Cooper Tire & Rubber Company, The Goodyear Tire & Rubber Company, Hankook Tire Co., Ltd., Kumho Tire Company Inc., Compagnie Générale des Établissements Michelin, Pirelli & C.S.p.A., Sumitomo Rubber Industries, Ltd., Toyo Tire Corporation., and The Yokohama Rubber Co., Ltd.

Total ELT generated (from available sources): Amount of ELT generated (in metric tons) according to the most reliable and comprehensive source available.

Total ELT recovered (excluding civil engineering and backfilling): Amount of ELT recovered (in metric tons), through material and energy recovery. This does not include any tires that are recovered for civil engineering and backfilling, abandoned, landfilled or stockpiled.

Total ELT recovered (including civil engineering and backfilling): Amount of ELT recovered (in metric tons), through material, energy recovery and civil engineering & backfilling. This does not include any tires that are abandoned, landfilled or stockpiled.

Types of vehicles:

- Passenger cars: road vehicles excluding motorcycles with a capacity of below nine people in total (i.e. nine seats or less - inspired by the OICA definition).

- Commercial vehicles: light duty commercial vehicles, coaches, buses, heavy duty vehicles such as trucks (inspired by the OICA definition). These will also include the OTR vehicles.

- Motorcycles: Two and three-wheeled motorized vehicles including mopeds, scooters and motorcycles.

Vehicles in use: All registered vehicles on the road during a given period-specific date (inspired by the OICA - definition).

INTRODUCTION

Vehicles at the end of their life are not being handled in an optimal way, resulting in loss of resources and pollution. Modern, low-emissions vehicles need light-weight materials, batteries and electronic components, which are dependent on imports and can be difficult to recycle.

The automotive industry is responsible for a large share of resource consumption, especially steel, aluminum, plastic, rubber, and glass, among others. Some newer models use carbon fibres to reinforce plastic parts – these novel materials can reduce carbon footprint and energy consumption but are challenging to recycle and can contaminate waste streams.

The course provides a better understanding of the current challenges in the processing of end-of-life vehicle waste, according to the ways of solving them through advanced waste recovery methods, and contributes to the change of European automotive waste management towards a more sustainable management of materials within the framework of the circular economy. Digital technologies are addressed, which ensure more efficient waste management in the automotive industry, improving recycling, facilitating the use of recycled materials by manufacturers, enabling better purchasing and sorting decisions by consumers, and improving waste sourcing options for recyclers.

The main aspects covered are:

- ☑ Waste recovery of end-of-life vehicles with a focus on End of life vehicles regulation in the EU, End-of-life vehicles management in the circular economy, and challenges in waste processing. Also, the materials from the automotive industry, their recovery rates and methods of recovery are addressed together with issues regarding the future of ELV Recycling.
- ☑ Advanced methods for recovery and reuse of used tires
- ☑ Advanced Technologies for Recovery of glass waste from the automotive industry
- ☑ The second chance at life of EV batteries through circular economy
- ☑ Smart waste management: Innovative technologies used in waste management, Robotic Waste Recycling System, AI based sorting technology for plastic waste.

The future of ELV recycling has high potential. Through advanced technologies, a circular economy approach, collaborative efforts, supportive policies and a conscious approach, the ELV recycling industry is poised for significant growth. By embracing these opportunities, we can create a more sustainable and responsible approach to end-of-life vehicle management, contributing to a greener and cleaner future.

1 WASTE RECOVERY OF END-OF-LIFE VEHICLES

1.1 END OF LIFE VEHICLES REGULATION IN EU

The Directive 2000/53/EC on end-of-life vehicles (ELV Directive) sets clear targets for ELVs and their components. It also prohibits the use of hazardous substances when manufacturing new vehicles (especially lead, mercury, cadmium and hexavalent chromium) except in defined exemptions when there are no adequate alternatives. [[1]].

Since ELV Directive was introduced, several amendments have been made. The EU has also introduced several related rules such as the Directive on the type-approval of motor vehicles regarding their reusability, recyclability and recoverability.

Amendments:

- Directive 2000/53/EU on end-of-life vehicles restricts the use of certain hazardous substances (lead, mercury, hexavalent chromium and cadmium) in vehicles put on the market after 1 July 2003. Possible exemptions for the use of these substances are set out in Annex II. It is regularly adapted to scientific and technical progress by the Commission according to Article 4(2)(b) of the Directive in order to address when the use of the restricted substances reflected in the exemptions has become avoidable or whether the scope of the exemptions can be narrowed.
- In March 2023, Delegated Directive 2023/544 amending Directive 2000/53/EC of the European Parliament and of the Council as regards the exemptions for the use of lead in aluminium alloys for machining purposes, in copper alloys and in certain batteries entered into force.

THE ACTUAL PROBLEMS

Vehicles at the end of their life are not being handled in an optimal way, resulting in loss of resources and pollution. Modern, low-emissions vehicles need light-weight materials, batteries and electronic components, which are dependent on imports and can be difficult to recycle.

Lack of circularity in design and production: Existing laws have not led to better eco-design of cars nor to an increase in use of recycled materials.

Poor quality of vehicle waste treatment: Low-quality scrap steel, insufficient separation of materials, low plastics recycling rates.

High dependency on imported raw materials: Automotive industry consumes vast amounts of raw materials, many of which (such as rare elements for electric motors) must be imported.

1/3 of vehicles go “missing”: Around 3.5 million vehicles disappear without a trace from EU roads each year - and are exported, or disposed of illegally.

Weak governance and lack of cooperation: Lack of financial accountability and not enough cooperation between manufacturers and recyclers.

1/3 of vehicles by mass are not regulated: Lorries, motorcycles, buses are not covered by the current end-of-life vehicles rules.

(Critical) raw materials: The production of vehicles is one of the most resource-intensive industries. The automotive industry in the EU is the N°1 consumer of aluminium (42%), magnesium (44%), platinum group metals (63%), natural rubber (67%) and rare earth elements (30% in 2025, and growing exponentially).

NEW END-OF-LIFE VEHICLES REGULATION

A review of the ELV Directive was launched in 2021, resulting in a proposal for a new regulation in 2023. On 13 July 2023 the Commission proposed a new Regulation on end-of-life vehicles, following a review. In line with the European Green Deal and with the Circular Economy Action Plan, the proposal for an ELV Regulation builds on and replaces two existing Directives: Directive 2000/53/EC on end-of-life vehicles and Directive 2005/64/EC on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability.

New rules for the design and end-of-life management of vehicles aim to protect the environment, decarbonise production and reduce raw material dependencies, benefiting EU industries.

THE EU PROPOSAL

➔ Design circular

Improve the rules on how cars must be designed to be easily dismantled:

- set minimum reusability, recyclability and recoverability rates
- car makers must give detailed instructions to replace and remove parts and components
- vehicles must come with a vehicle circularity passport.

➔ Use recycled content

- 25% of the plastic used to build a new vehicle must be recycled
- recycled content levels must be declared.

➔ Collect more and smarter

To put a stop to “missing” ELVs, enforce the current rules and increase transparency:

- connected national vehicle registration systems
- ban on exporting vehicles that aren’t roadworthy
- more inspections and fines
- clearer distinction between old and end-of-life vehicles.

➔ Treat better

Recover more and better-quality raw materials through:

- stricter definition of recycling, landfill restrictions
- mandatory removal of valuable parts, components and materials
- 30% of plastics must be recycled
- stop mixing ELV waste with other waste
- incentives to encourage the sale of spare parts.

➔ Make producers responsible

Better governance, better cooperation, more circularity:

- strengthen "Extended Producer Responsibility" to encourage better quality waste treatment
- improve cooperation between manufacturers and recyclers.

➔ Cover more vehicles

Gradually extend the scope of the rules for:

- all lorries, buses and motorcycles will be treated at authorised facilities
- only roadworthy heavy duty vehicles may be exported.

THROUGH THESE CHANGES, IT IS ESTIMATED THAT BY 2035 THE FOLLOWING WILL BE ACHIEVED:

- ☑ **12.8 million tons less CO2 emitted** worth 2.9 billion EUR.
- ☑ **3.8 million more ELVs collected and treated in the EU** including motorcycles, lorries, buses and vehicles that could have been exported or dismantled illegally
- ☑ **350 tons of rare earth materials collected for reuse and recycling** significantly contributing to the EU's strategic autonomy
- ☑ **5.4 million tons of materials recycled at higher quality or re-used** including plastics, steel, aluminium, copper and critical raw materials
- ☑ **22,000 new jobs will be created in the EU** including 14,000 jobs for SMEs, contributing to a stronger and modernised dismantling and recycling industry
- ☑ **Lower prices for second-hand parts and components** meaning it will be cheaper to maintain and repair vehicles
- ☑ **Stepping up in the area of exported used vehicles:** Over 800,000 used vehicles are exported from the EU each year, mainly to Africa. Many of these vehicles are highly polluting and dangerous (causing traffic deaths) given their age. The export of end-of-life vehicles is already banned. The new, stronger regulation and more traceability will ensure that only high-quality, technically fit European vehicles will be exported to consumers in 3rd countries.

1.2 END-OF-LIFE VEHICLES MANAGEMENT IN CIRCULAR ECONOMY

Vehicles are complex products, increasingly greener and smarter, comprising a diverse range of parts composed of several materials for which recycling technologies may not yet be available. For example, some newer models use carbon fibres to reinforce plastic parts – these novel materials can reduce carbon footprint and energy consumption but are challenging to recycle and can contaminate waste streams.

The automotive industry is responsible for a large share of resource consumption, especially steel, aluminum, plastic, rubber, and glass, among others.

The industry generates about five percent of industrial waste in the entire world,* and with increasing demand for electric vehicles (EVs), battery material consumption grows significantly.

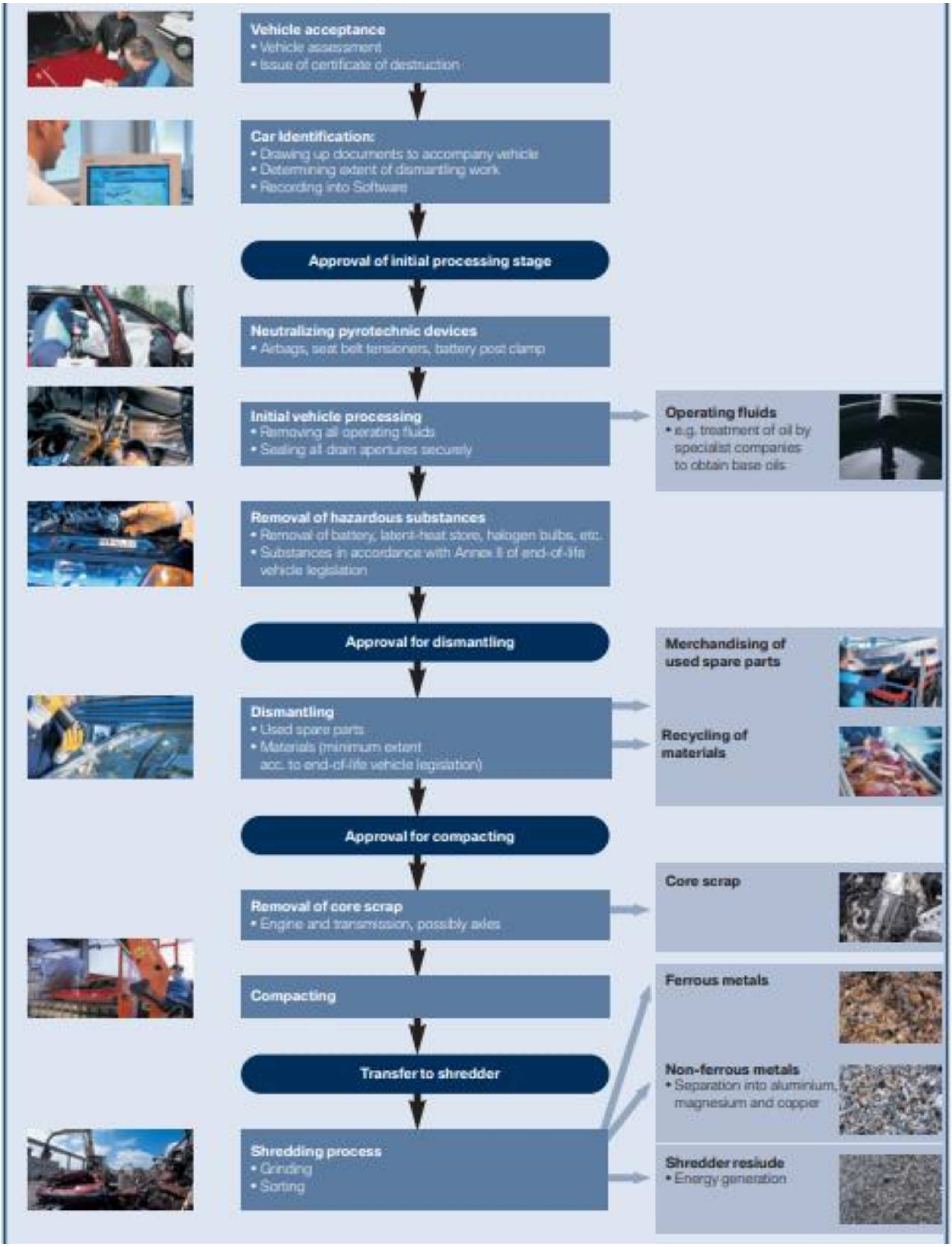
Circularity is the key in order to tackle the environmental challenges by maximizing the value retention throughout the entire life cycle of products and materials. At the same time, the use of secondary materials avoids excessive use of finite natural resources and minimizes waste at a vehicle's end of life while also reducing emissions from their manufacturing process. According to the Ellen MacArthur Foundation, the implementation of circular business practices could save to 45% of carbon emissions and 90% of wasted materials. More than that, by implementing a data-driven "R-strategy" (reuse, remanufacturing, recycling), a circular economy does not only help enterprises meet their sustainability goals but also generate new business opportunities for the industry.

Auto makers invest around one-third of the EU's R&D spend, much of which is pumped into technologies to boost vehicle circularity. However, the Commission's proposal risks duplicating or complicating existing rules and industry best practices, hindering these vital investments. Instead, the regulation should better account for vehicles' increasing complexities and specificities, including longevity, durability, and reparability.

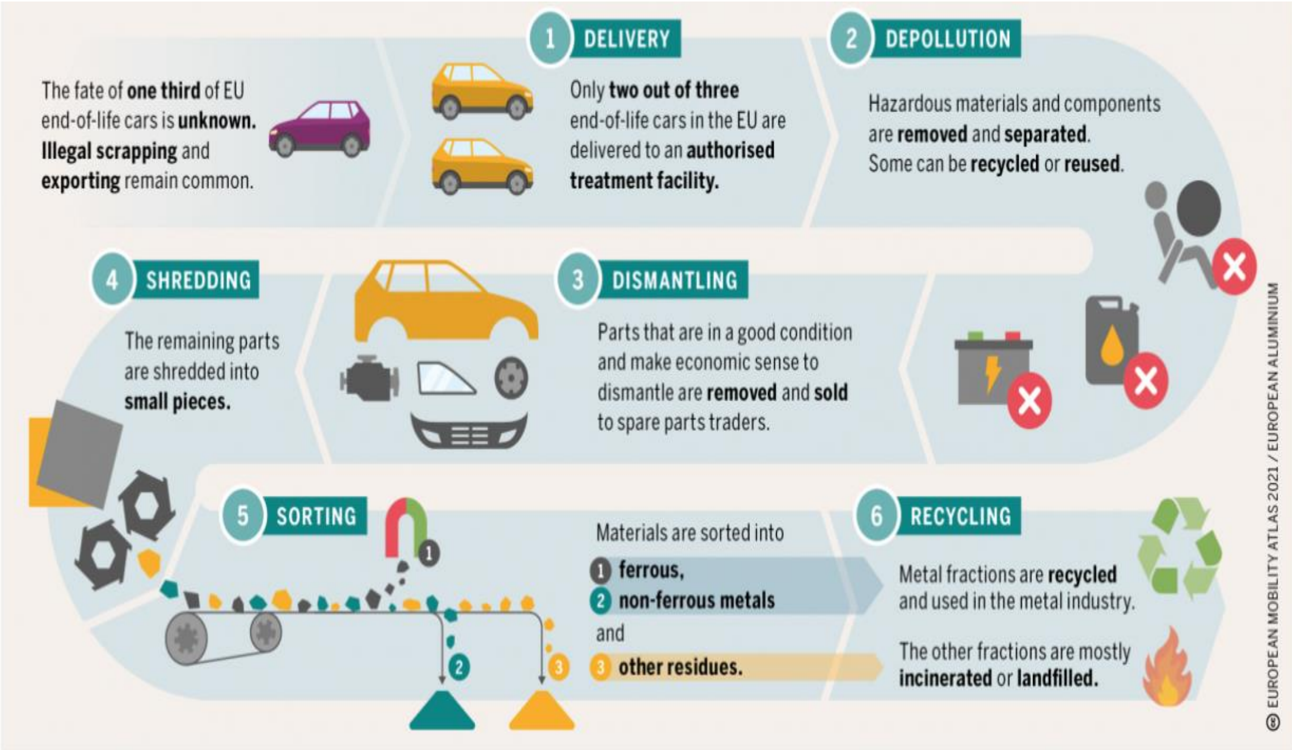
END-OF-LIFE VEHICLES are vehicles that have ended their useful life and are processed as waste. In practice, they are dismembered, shredded or otherwise disposed of.

The **DISMANTLING PROCESS** consist in [2]:

1. **Collection of ELVs:** network for collecting ELVs, ensuring a steady supply of vehicles for recycling.
2. **Tire removal and recycling:** Tires, another significant component of ELVs, are extracted and sent for recycling. This process contributes to reducing the environmental impact of waste tires and promotes resource conservation.
3. **Battery removal and recycling:** This step involves carefully removing and recycling the vehicle's battery. Also, involves strict protocols to ensure these hazardous components' safe handling and recycling.
4. **Depollution of the vehicle:** advanced de-pollution techniques to eliminate any remaining hazardous substances from the vehicle, including harmful chemicals and pollutants. Depollute the vehicles such as engine oil, transmission fluid, and coolant are drained and safely disposed of, preventing any potential environmental contamination.
5. **Airbag removal and disposal:** Airbags, crucial for occupant safety, are meticulously removed and disposed of following environmental regulations.
6. **Dismantling of vehicle components:** The vehicle is then systematically dismantled, carefully separating each component for recycling or disposal. This process ensures maximum utilization of valuable materials and reduces waste generation.
7. **Sorting and segregation of materials:** After dismantling, the various materials, such as metals, plastics, and glass, are sorted and segregated. MSTI utilizes cutting-edge technology to identify and categorize these materials accurately, enabling proper recycling or disposal.



1-1. Figure_ End-of-life vehicle recycling proces [www.bmwgroup.com]

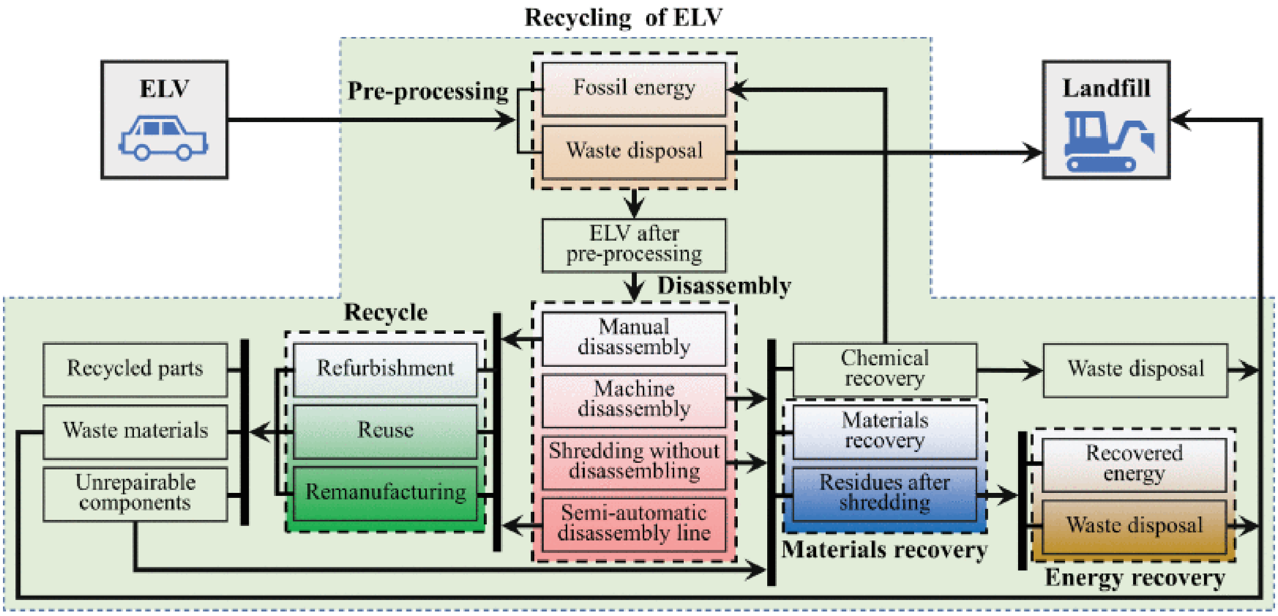


1-2. Figure_ Exemples of a modern combustion engine cars' subcomponents that can be recycled »A car's last journey«

[»A car's last journey«picture: Heinrich-Böll-Stiftung European Union, licence: CC-BY-SA 4.0 https://eu.boell.org/en/end-of-life-vehicles-final-destination]

During the dismantling phase, spare parts of the vehicle may be separated and reused for repairing vehicles in service (reuse operation). The rest of the dismantled vehicle will undergo recycling operations, be used for producing energy (energy recovery operation) or finally disposed [3], [4].

EU Member States and EEA/EFTA countries yearly report data on the total vehicle weight and number of end-of-life vehicles and rates for 'total reuse and recycling' and 'total reuse and recovery'. The data cover end-of-life passenger cars and light goods vehicles such as vans and pick-ups. Information and data are based on Directive 2000/53/EC on End-of-Life Vehicles and Commission Decision 2005/293/EC, which lays down rules on monitoring the reuse/recovery and reuse/recycling of end-of-life vehicles according to the definition of these operations in Directive 2000/53/EC.



1-3. Figure_Typical mode of ELV disassembly and recycling.

[https://www.repsol.com/en/sustainability/circular-economy/our-strategy/index.cshtml]

AUDI CLOSED MATERIAL LOOPS: THE MATERIALLOOP PILOT PROJECT

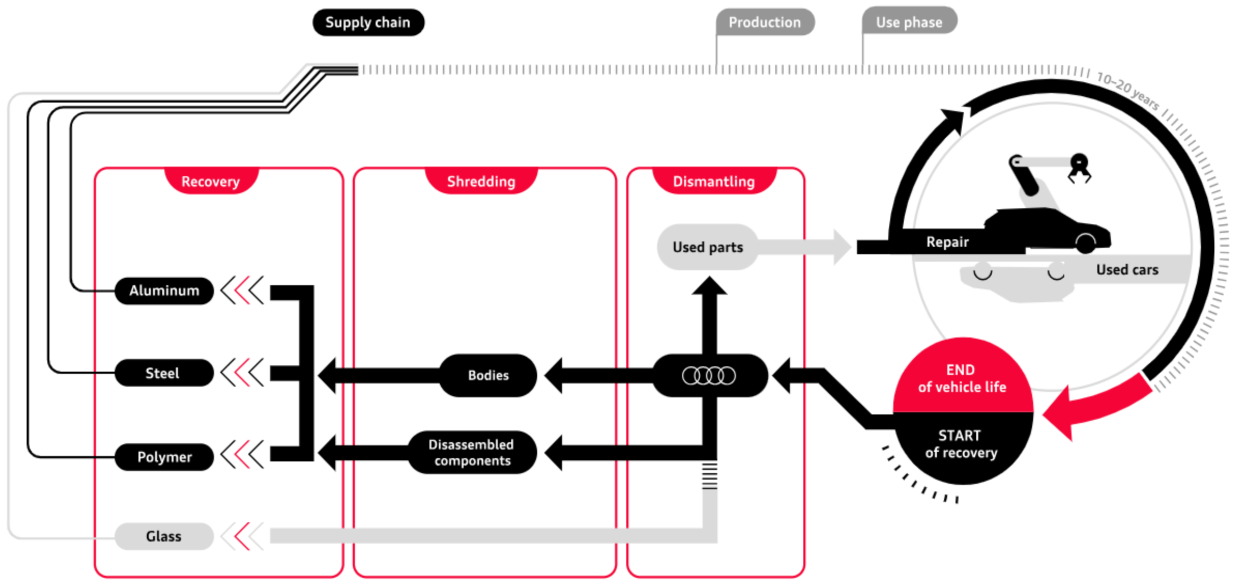
As part of a pilot project involving 100 used vehicles, Audi is now looking to forge new paths and aiming to ensure that the greatest possible proportion of materials make their way back into the automotive value chain. In the future, a growing number of material cycles are to be closed on balance in collaboration with partner companies.

The MaterialLoop project provides Audi with a wide range of new insights on its journey toward implementing a circular economy.

In the MaterialLoop project, Audi is testing a closed loop for end-of-life vehicles together with 15 project partners [5].

THE GOALS: first, to return as much material as possible from 100 end-of-life vehicles to the automotive cycle without loss of quality (avoiding downcycling).

Second, to build knowledge with regard to design and engineering: how and from which materials should components be designed and manufactured in the future so that they can be kept in the automotive cycle?



1-4. Figure_AUDI MaterialLoop pilot project

[https://www.audi.com/en/company/sustainability/core-topics/value-creation-and-production/material-loop.html]

After removing components that are suitable for reselling as used parts, the focus of the MaterialLoop project was on recycling the material groups steel, aluminum, plastic and glass.

1.3 CHALLENGES IN THE WASTE PROCESSING OF END-OF-LIFE VEHICLES

During the course of the late 1980s and early 1990s EU Member States were facing several challenges in the waste processing of end-of-life vehicles. Therefore, Directive 2000/53/EC [[6]] and Commission Decision 2005/293/EC provide MEASURES TO REDUCE ENVIRONMENTAL HARM due to inappropriate depollution and disposal of car bodies:

- Charges on recycling and disposal services provided limited motivation to the last owner to abide by the law when disposing end-of-life vehicles. Directive 2000/53/EC obliges the Member States to take the necessary measures to ensure that all end-of life vehicles are transferred to authorised treatment facilities.
- In order to reduce the very high volumes of shredding process residues, containing several pollutants and chemicals, Directive 2000/53/EC established targets for mandatory de-pollution, as well as quantified targets for reuse, recycling and recovery of vehicles and their components, pushing producers to design and manufacture vehicles with a view to their recyclability.
- Different disposal conditions amongst EU Member States were causing high shares of import/export of end-of-life vehicles inside the EU. To monitor this

practice, in addition to the aforementioned measures, the recycling and recovery rates from exported vehicle parts are credited to the exporting Member State, according to Commission Decision 2005/293/EC.

1.3.1 FUTURE OF ELV RECYCLING

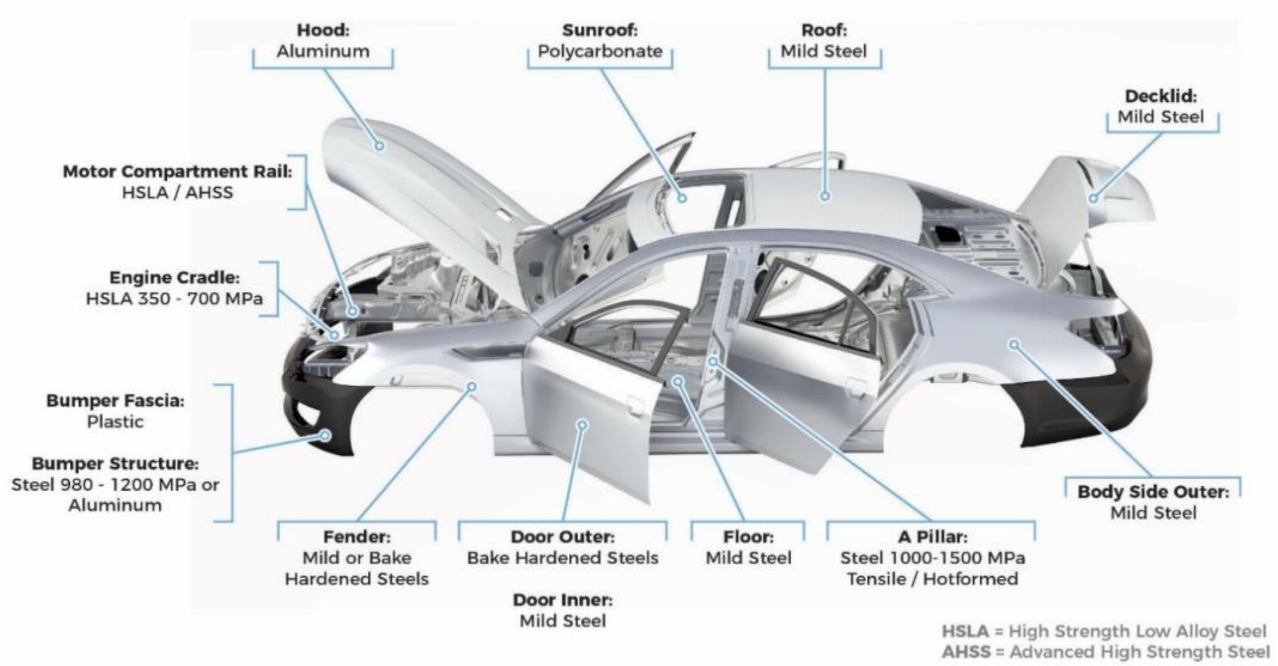
The future of ELV recycling is poised for exciting developments, driven by ongoing innovations and growing environmental consciousness; the key aspects that highlight the potential of the ELV recycling industry are [[7]]:

1. **Circular Economy Approach:** The concept of a circular economy, which aims to minimize waste and maximize resource efficiency, will play a significant role in the future of ELV recycling. Instead of treating ELVs as waste, they will be viewed as a valuable resource that can be reused, remanufactured, or recycled. In addition, this approach will promote the recovery of materials and components from ELVs, reducing the dependence on virgin resources.
2. **Advanced Recycling Technologies:** Technological advancements will continue to revolutionize ELV recycling processes. Innovations such as baling and separation techniques, advanced material identification and sorting systems, and dismantling technologies will enhance efficiency and resource recovery rates. These advancements will lead to more cost-effective and environmentally friendly recycling methods.
3. **Electric Vehicle Battery Recycling:** As electric vehicles gain popularity, recycling lithium-ion batteries will become increasingly important. Developing efficient and sustainable methods for recycling electric vehicle batteries will be a key focus. This will involve extracting and recovering valuable metals, such as lithium, cobalt, and nickel, from spent batteries. Effective battery recycling will support the growth of the electric vehicle industry and help address concerns related to the disposal of electric vehicle batteries.
4. **Collaboration and Partnerships:** Collaboration between automobile manufacturers, recycling facilities, governments, and research institutions will be crucial for the future of ELV recycling. Partnerships can facilitate sharing of knowledge, resources, and best practices, enabling the development of standardized recycling processes and establishing a comprehensive recycling infrastructure.
5. **Policy and Regulatory Support:** Governments worldwide recognize the importance of sustainable waste management, including ELV recycling. Policy and regulatory frameworks will continue to evolve to support and encourage responsible ELV recycling practices. This may involve implementing extended producer responsibility (EPR) programs, financial incentives, and stricter regulations on the disposal of ELVs.
6. **Public Awareness and Participation:** Increasing public awareness about the benefits of ELV recycling will be vital for its future growth. Educating consumers

about the importance of proper ELV disposal, recycling options, and the environmental impact of their choices will encourage more active participation in recycling initiatives. Consumer demand for environmentally friendly products and services will also drive automobile manufacturers to adopt more sustainable practices, including the design of easily recyclable vehicles.

1.4 AUTOMOTIVE MATERIALS, THEIR RECOVERY RATES AND METHODS OF RECOVERY

The most used automotive materials are presented in 1-5. Figure.



1-5. Figure_ Materials Used Most Commonly for Major Vehicle Structure Components in the Current Fleet
[source: https://www.cargroup.org/wp-content/uploads/2017/07/Technology_Roadmaps.pdf]

In present, the most commonly used automotive materials include [8]:

Mild Steel: Mild steels are easy to form, which makes them a top choice for automotive parts manufacturers using cold stamping and other dated manufacturing processes. They have a maximum tensile strength of 270 MPa.

High Strength Steel (HSS): uses traditional steels and remove carbon during the baking cycle. This means softer steels can be formed and then baked into harder metals. Typical tensile strength grades range from 250 to 550 MPa.

High Strength Low Alloy (HSLA): HLSAs are carbon manganese steels strengthened with the addition of a micro alloying element such as titanium, vanadium, or niobium. These have a tensile strength up to 800 MPa and can still be press formed.

Advanced High Strength Steel (AHSS): Advanced high strength steels generally yield strength levels in excess of 550 MPa. They are composites made of multiple metals, then heated and cooled throughout the manufacturing process to meet a part's specifications.

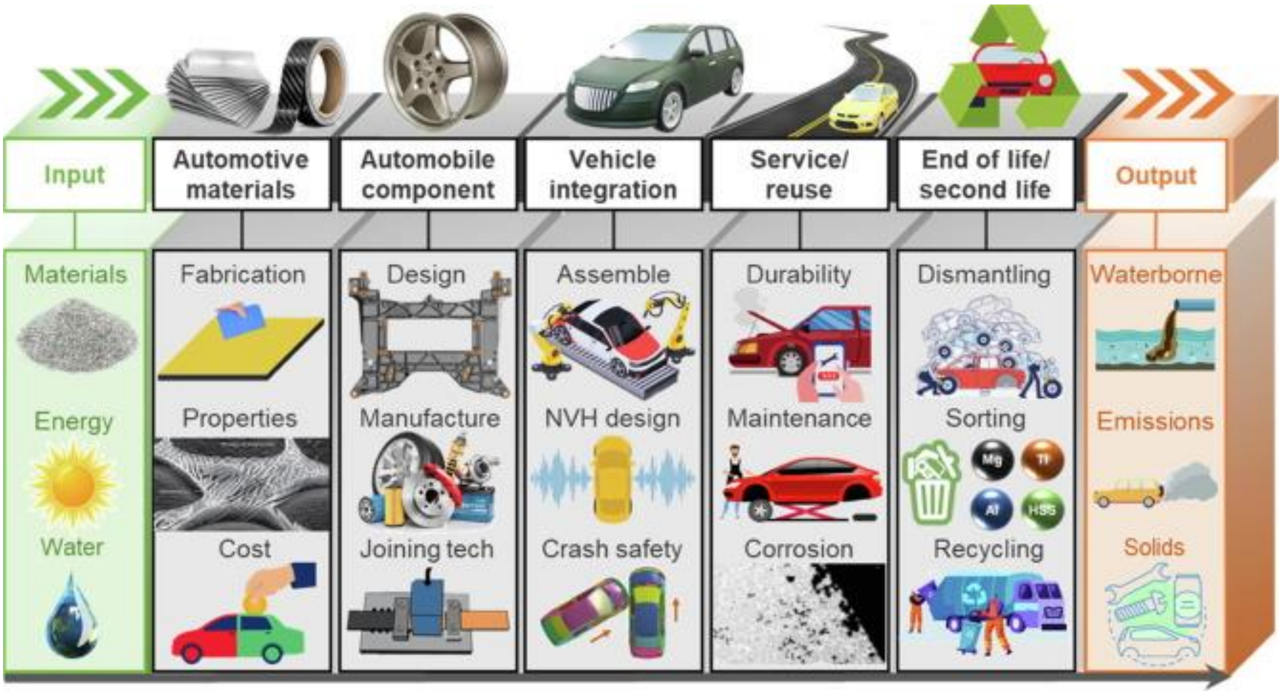
Ultra High Strength Steel (UHSS): These follow similar properties as AHSS but maintain strength levels of at least 780MPa.

Boron/Martensite: Martensite is the hardest and strongest form of steel, but it's also the least formable. It shares properties with boron, which has a tensile strength of around 1,200 to 1,800 MPa. These are usually combined with softer steels to form composites.

Aluminum 5000/6000 (AL 5000/6000): 5000-series aluminum is alloyed with magnesium. 6000-series aluminum contains both silicon and magnesium which forms magnesium silicide and makes the aluminum alloy heat-treatable.

Magnesium: Magnesium is an attractive material for automotive use because of its light weight. When alloyed, magnesium has the highest strength-to-weight ratio of all structural metals.

Carbon Fiber Reinforced Plastic (CFRP): CFRPs are extremely strong, light plastics which contain carbon fibers to increase strength. They are expensive to produce but will have a growing demand in the future automotive industry as costs are reduced.



1-6. Figure_The entire life cycle of automotive materials [9]

Type of materials, their recovery rates and methods of recovery for ELVs are centralized in Table 1.1 [10].

Table 1.1_ ELV: Type of materials, their recovery rates and methods of recovery

Type of material	Recycling rate using BAT	Recovery rate using BAT	Recovery rate from network	Recovery method
Ferrous metals – Steel	100%	100%	90 - 98%	Shredding & remelting
Ferrous metals – Cast iron	100%	100%	80 - 90%	
Non ferrous metals – Pb	100%	100%	80 - 98%	Dismantling, mechanical separation & remelting Shredding & remelting
Non ferrous metals – Al	100%	100%	80 - 95%	
Non ferrous metals – Cu, Zn	100%	100%	60 - 80%	
Thermoplastics (unfilled)	100%	100%	50 - 70%	Dismantling, separation & dedicated recycling processes Shredder light fraction recycling Incineration
Thermoplastics (glass filled)	67%	100%	50 - 70%	
Thermosets (unfilled)	100%	100%	50 - 70%	Dismantling, separation & dedicated recycling processes Shredder light fraction recycling Incineration
Thermosets (glass filled)	67%	100%	50 - 70%	
Elastomers	80%	100%	90 - 98%	Dedicated recycling processes Shredder light fraction recycling Incineration
Glass	100%	100%	50 - 100%	Remelting
Safety glass	94%	94%	50 - 94%	Separartion& remelting
Oils	100%	100%	50 - 100%	Refining Incineration
Other fluids (lubricants, all chemical fluids)	83%	83%	90 - 98%	Dedicated recycling processes
Modified organic natural materials (leather, wood, cotton fleece,…)	95%	100%	50 - 70%	Dedicated recycling processes Shredder light fraction recycling
Carbon or natural reinforced polymers	67 - 80%	80-100%	50 - 70%	Dedicated recycling processes
Electronic and electric	80%	98%	60 - 85%	Sorting and dedicated recycling processes
Ceramics	43%	43%	20 - 40%	Dedicated recycling processes
Silicone fiberglass	80%	80%	50 - 70%	Dedicated recycling processes

1.5 AUTOMOTIVE WASTE PROCESSING OPERATIONS

Directive 2000/53/EC on end-of-life vehicles is sometimes using different definitions for the classification of operations of: **reuse, backfilling, energy recovery, recycling and recovery** according to the definitions in the Waste Framework Directive (WFD).

In the following lines, a summary of the definitions in the end-of-life context is provided:

Reuse has a similar definition as in WFD; in the end-of-life context, it means that spare parts coming from dismantled cars are reconditioned and used as replacement of broken parts of vehicles in service; the wording reuse implies that the spare part is functionally used for the same purpose for which the part was designed for.

Backfilling means the use of non-hazardous materials, arising from dismantling or shredding, for engineering purposes as landscaping or similar, for instance car glass; the definition of reuse cannot apply because these materials or parts are used for a different purpose than the one for which they were designed. This definition is coherent with the one used in the WFD.

Energy recovery means the use of combustible waste as a means to generate energy through direct incineration with or without other waste but with recovery of the heat, coherently also with the WFD

Recycling, in the end-of-life vehicles context, means any reprocessing in a production process of the waste materials either for the original purpose or for other purposes, excluding energy recovery. Differently from the WFD, it includes also backfilling operations.

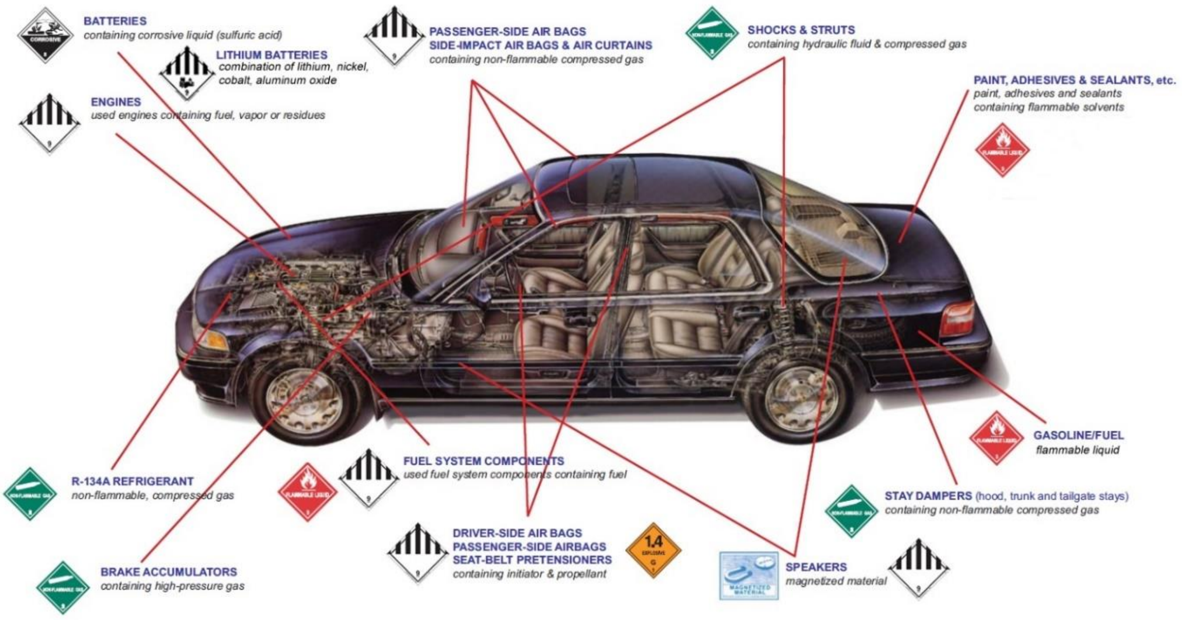
Recovery, in the end-of-life vehicles context, is any operation which can be classified as recycling (including backfilling) or energy recovery; the definition is therefore coherent with the one in the WFD.

The definition of recycling differs between Directive 2000/53/EC on end-of-life vehicles (ELV directive) and the WFD due to the different classification of backfilling:

- ⇨ In the ELV directive, backfilling is part of the recycling waste management operations;
- ⇨ In the WFD, backfilling is excluded from recycling and is only included in recovery waste management operations. These definitions are used for calculating the target rates monitored in Directive 2000/53/EC on end-of-life vehicles [11].

1.5.1 PRETREATMENT

In a preliminary step, all pyrotechnic components such as airbags, battery safety terminals (BST) or safety belt pretensioners are triggered for safety reasons. Special devices are then used to remove all operating fluids. Hazardous materials commonly found in vehicles are shown in 1-7. Figure [12].



1-7. Figure_ Hazardous materials commonly found in vehicles
[https://www.labelmaster.com/content/files/images/content-pages/industry/automotive/hazardous-materials-commonly-found-in-vehicles.jpg]

This stage includes siphoning off air-conditioning system refrigerant and brake fluid, draining radiator coolant, motor oil and transmission oil, and extracting any remaining fuel using a special drilling machine with a draining device. The various fluids are kept separate and placed into containers according to type for processing or recycling by specialised facilities.

Removing operating fluids ensures that potentially environmentally harmful fluids and substances cannot cause ground, water or air contamination in subsequent stages of recycling.

1.5.2 HIGH-END RECYCLING: REUSE OF COMPONENTS AND PARTS

In the next stage, the recycling specialists determine which of the vehicle's parts are suitable for assignment to "highend recycling", or re-utilising a part or component for its original function. Overhauling a component and placing it back into service thus represents the ideal case in terms of recycling.

Replacement engine production at the **BMW LANDSHUT PLANT** provides the most obvious example of highend recycling. The wide variety of existing reconditioned engines includes 30-year-old four-cylinders used in the old BMW 02 Series, various high-performance engines from the M models, 12-cylinder engines and powerplants from contemporary series. The 15,000 engines reconditioned each year by the facility represent an important constituent of the BMW Group replacement parts programme, which not only encompasses additional mechanical components such as gearboxes, clutches and differentials, but also electro-mechanical and electronic components, including generators, starters, control units and instrumentation.

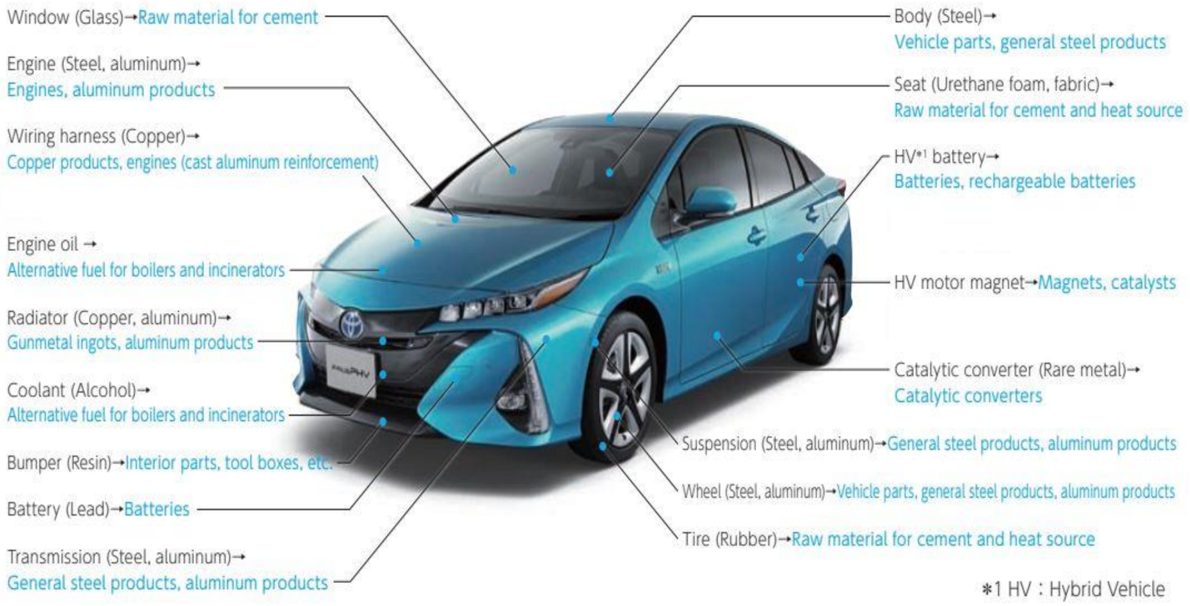
A total of around 2000 different parts are available from 150 product groups. These parts, which are available through dealerships, offer customers the same guarantees and quality as new parts for as little as half the price. Reconditioning is also of significant benefit to the environment, since up to 60 per cent of certain disused parts is recovered in the process of returning them to their original function.

1.5.3 MATERIAL RECYCLING FOR METAL, GLASS AND PLASTICS

These complex components are not the only automobile parts that go through a careful dismantling process. Those parts of the car that are made of recyclable materials are also selectively dismantled, sorted and collected according to type, a practice that is now even more important in view of EU guidelines. These specify that, beginning in 2006, 85% of an ELV by weight must be reused as parts or material. This requirement has long been fulfilled for metallic materials, which pertains not only to body steel and wiring harness copper, but also to materials such as the aluminium used in the undercarriage and magnesium employed in the instrument panel. Processing aluminium and magnesium from primary raw materials requires a significant amount of energy.
However, since both of these lightweight metals can be recycled using a fraction of the energy needed to produce them in the first place, they are among the most sought-after secondary raw materials.
Glass and a number of large plastic components can also be recovered and placed back into the production cycle.

1.5.4 PARTS RECYCLED FROM END-OF-LIFE VEHICLES

ELV are the most recyclable consumer products, which can provide more than 14 million tons of steel to the steel industry every year. Some examples of parts being recycled from end-of-life vehicles are presented in 1-8. Figure.



1-8. Figure_ Recycling posibilities of end-of-life vehicle

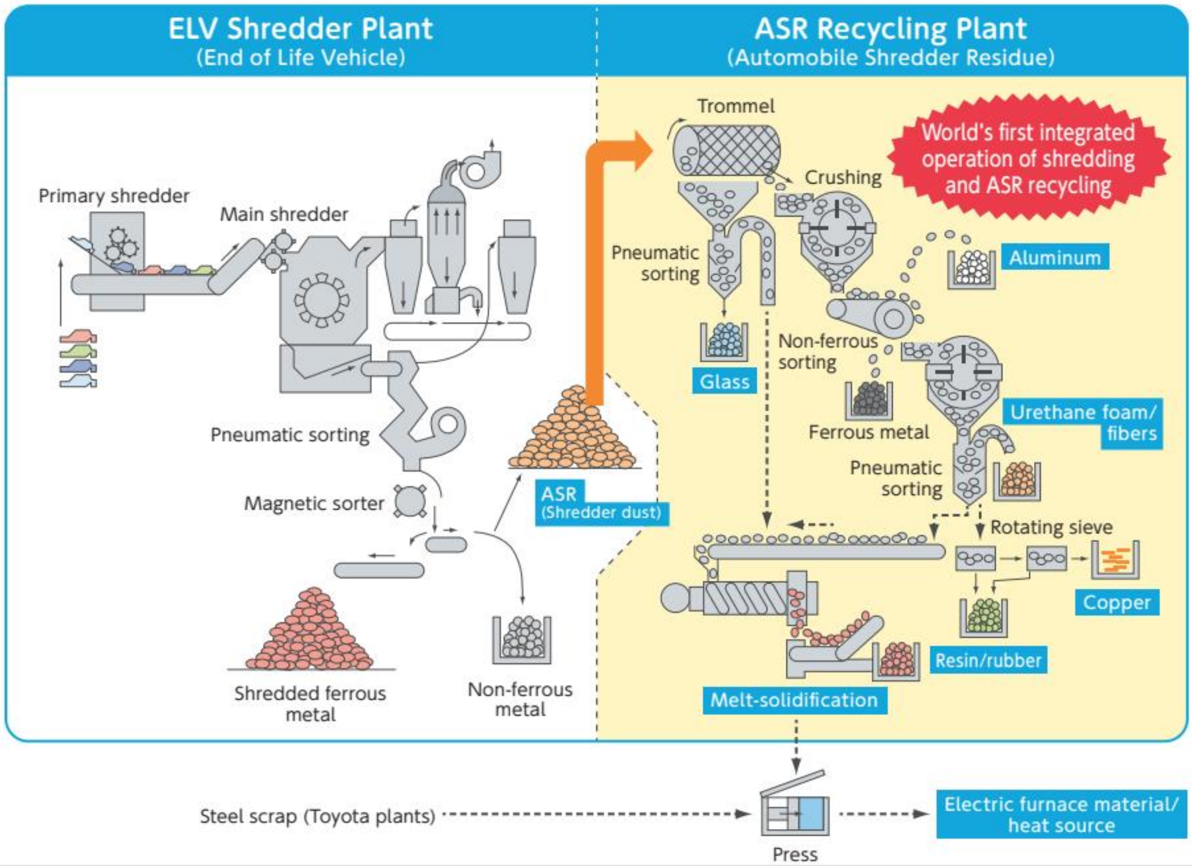
[https://global.toyota/pages/global_toyota/sustainability/report/kururisa_en.pdf]

1.6 ADVANCED SORTING TECHNOLOGY FOR AUTOMOTIVE SHREDDER RESIDUE (ASR)

After ELVs have been cleared of any polluting materials and stripped of parts that can be reused or recycled, the shells are crushed and shredded. Metals and plastics are separated out from the shredded matter, leaving a substance called ASR – Automotive Shredder Residue. ASR recycling deals with all the light fractions left over from recycling ELVs. This material also known as Shredder Light Fraction (SLF), auto or car fluff make up as much as 25 % of the ELVs weight and contains many different materials: plastics, rubber, glass, sand, textiles, wood, metals, and dust [[13]].

ASR recycling process downsizing the material to sort out materials for recycling and/or produce a fraction suitable as alternative fuel. In order to use automobile shredder residue completely, it is necessary to recycle it into the basic materials of products.

Since separation of constituents is required to raise their purity, Toyota developed special sorting technologies for ASR (Automotive Shredder Residue) recycling plants using wind and magnetism to make shredder residue reusable.



1-9. Figure_ Special sorting technologies for ASR at Toyota

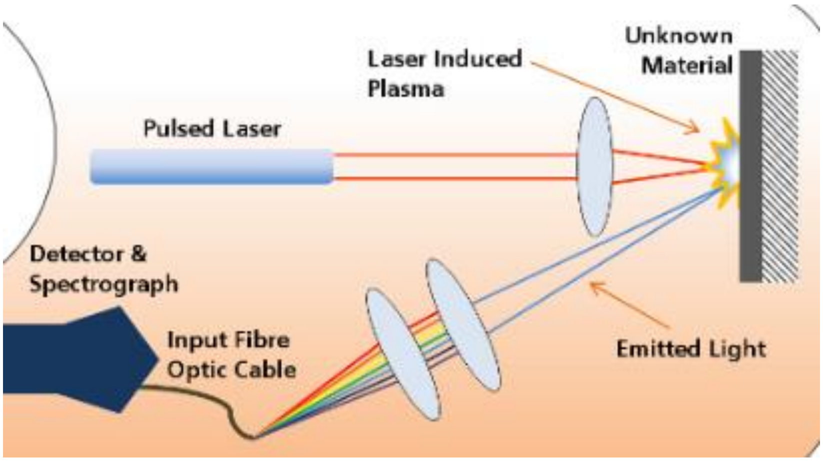
[https://global.toyota/pages/global_toyota/sustainability/report/kururisa_en.pdf]

1.6.1 LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS) LIBS BASED SENSOR SORTING TECHNOLOGY

An example from Austin AI's product portfolio is the LIBS based sensor sorting technology- which is a key part of Aluminum recyclers' sorting line. LIBS enhances the added value of sorted fractions – aiming for zero carbon emissions and circular economy. In Austin AI's wheel sorter, used for end-of-life vehicles (ELV), LIBS is primarily the technology used [14].

LIBS Modern sensor-based sorting technologies offer much-enhanced sorting functionality, sorting wrought Al alloy scrap into different grades including 5xxx and 6xxx series alloys and removing unwanted product.

Laser-induced breakdown spectroscopy (LIBS) is a type of atomic emission spectroscopy which uses a highly energetic laser pulse as the excitation source.

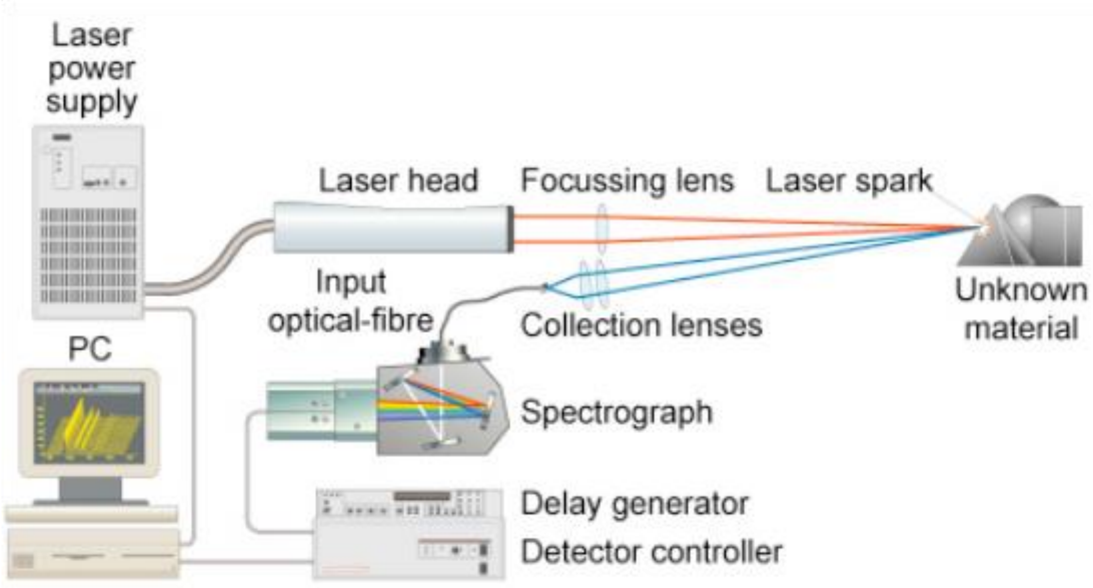


1-10. Figure_ Laser-induced breakdown spectroscopy (LIBS)

[https://austinai.com/libs-tech]

The laser is focused to form a plasma, which atomizes and excites samples. In principle, LIBS can analyze any matter regardless of its physical state, be it solid, liquid or gas.

Because all elements emit light of characteristic frequencies when excited to sufficiently high temperatures, LIBS can (in principle) detect all elements. If the constituents of a material to be analyzed are known, LIBS may be used to evaluate the relative abundance of each constituent element, or to monitor the presence of impurities. LIBS operates by focusing the laser onto a small area at the surface of the specimen; when the laser is discharged it ablates a very small amount of material, in the range of nanograms to picograms, which generates a plasma plume with temperatures in excess of 100,000 K.



1-11. Figure_ Schematic illustration of LIBS detection
[https://austinai.com/libs-tech]

PARTICULARITIES OF LIBS:

- During data collection, typically after local thermodynamic equilibrium is established, plasma temperatures range from 5,000–20,000 K.
- At the high temperatures during the early plasma, the ablated material dissociates (breaks down) into excited ionic and atomic species.
- During this time, the plasma emits a continuum of radiation which does not contain any useful information about species presented, but within a very small timeframe the plasma expands at supersonic velocities and cools.
- At this point the characteristic atomic emission lines of the elements can be observed.
- The delay between the emission of continuum radiation and characteristic radiation is in the order of 10 μs, this is why it is necessary to temporally gate the detector.
- Scrap must be of appropriate quality before it can be melted down.
- To obtain this level of quality, all adherent materials must be removed.
- Depending on scrap type, aluminum losses of about 2% to10% may be incurred during separation of aluminum from other materials.
- A certain degree of material loss is inevitable with industrial processes but, because of aluminum's high intrinsic value, all efforts are directed at minimizing losses.
- For example end-of-life products are often not mechanically separable into single material output fractions. A dilution of foreign materials within each output is the result.
- The treatment of scrap is a joint undertaking by the aluminum recycling industry and specialized scrap processors.

- Almost all aluminum used commercially contains one or more alloying elements to enhance its strength or other properties.
- Aluminum recycling therefore contributes to the sustainable use of copper, iron, magnesium, manganese, silicon, zinc and other elements.

Implementing new technology in the form of LIBS and XRF sorting is maximizing recycling quantities accordingly and opens up up-to-date eco efficient process optimization.

1.6.2 HIGH END X-RAY TECHNOLOGY

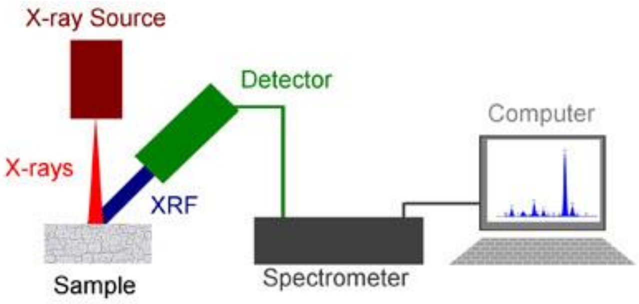
X-Ray Modern sensor-based sorting technologies offer much-enhanced sorting functionality, sorting scrap into different grades by elements like Cu, Zn etc. and removing unwanted products.

1.6.2.1 X-RAY FLUORESCENCE TECHNIQUE (XRF)

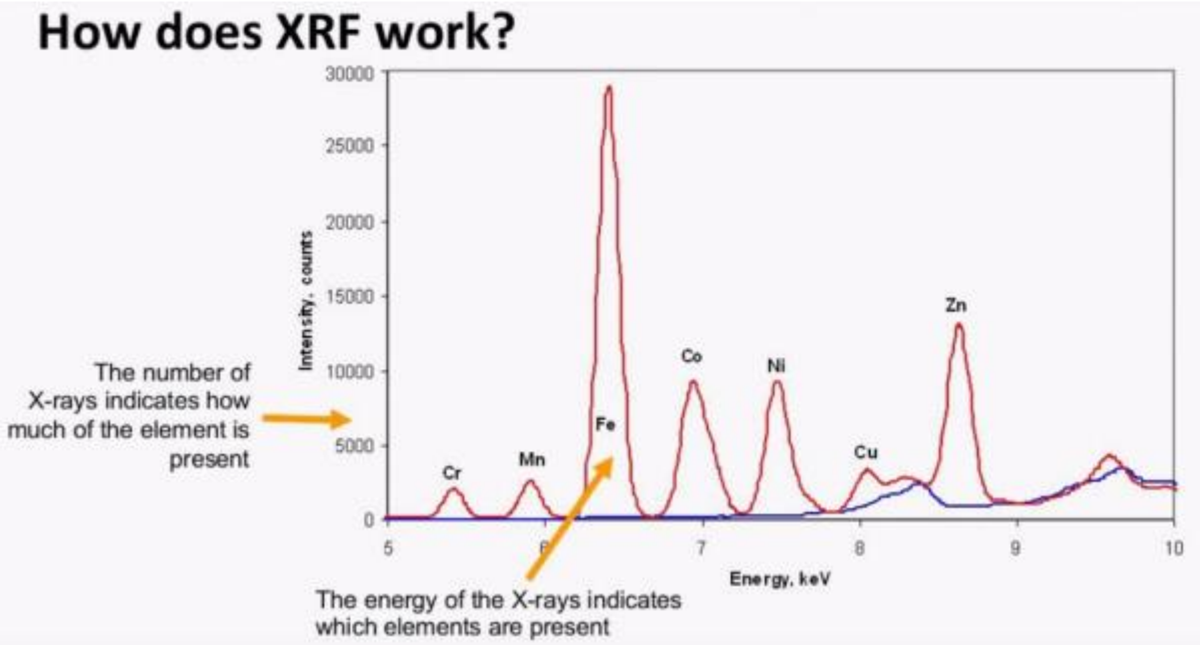
Nearly all elements, from iron to copper to nickel to tungsten, have unique and known X-ray signatures.

- When an X- or Gamma-ray is absorbed by an element, the element fluoresces, or emits energy. Inner-shell atomic fluorescence produces the X-ray signature, and can be "captured" and reported.
- XRF analyzers do both tasks: they provide the incident X-rays that generate the excitation in the atoms and then detect the fluorescence from most of the elements in the sample material
- In the recent past, sorting Aluminum alloys by means of XRT (X-ray-Transmission) technology has been tried. However, this expensive sensor technology (based on the physical property of material density) is not precise enough for specific alloy sorting.
- Additionally, extra material preparation stages like sizing for XRT sorting is costly and time consuming.
- Sorting with XRT has demonstrated to be cost inefficient and yielding poor product quality when used beyond the stage of rough sorting light and heavy metal alloys commonly found in shredder scrap.
- The scrap processor to scrap consumer business link is therefore in need of a better bridge by which they may conduct their trade.
- In the Austin AI model, the XRT approach is thus followed by XRF (X-Ray Fluorescence) technique.
- Using the XRF sensor technology, aluminum alloys can be classified cost efficiently, at a high quality, and at an economically viable throughput performance.
- Different than XRT, which results merely in black white imaging as sorting criteria, XRF sensing allows the definition of plain material composition according to the atomic elements table.

- XRF, and its partner technology in Austin AI first-of-its-kindscrap metal processing line, LIBS, are elemental analyzers that use the chemistry of the target material for identifying or sorting criteria.
- For example, the XRF technology has proven usage for the scrap metal processors in sorting their Zorba und Zurik. XRF extracts Zn, Cu, Ni, Fe, etc., from the Zorba; and extract only PCB's or Cu from Zurik material.



1-12. Figure_ XRF Diagram
[https://austinai.com]



1-13. Figure_ Schematic illustration of XRF detection
[https://www.austinai.com/x-ray-tech]

XRF Sensor-based, density sorting alone is not good enough for most aluminum recycling applications.

1.7 INTERNATIONAL DISMANTLING INFORMATION SYSTEM - IDIS

IDIS, the International Dismantling Information System was originally developed by 10 European car manufacturers and was intended to provide dismantlers with valuable information for an environmentally-sound treatment of end-of-life vehicles (ELV). This has subsequently grown into the IDIS 2 Consortium representing 23 automotive manufacturers, including all major manufacturers from Europe, Japan, Korea and the United States [[15]].

The IDIS 2 Consortium has developed software which allows visualisation of the components of cars and contains a database of 450 vehicles (around 30 000 parts) for all 23 manufacturers.

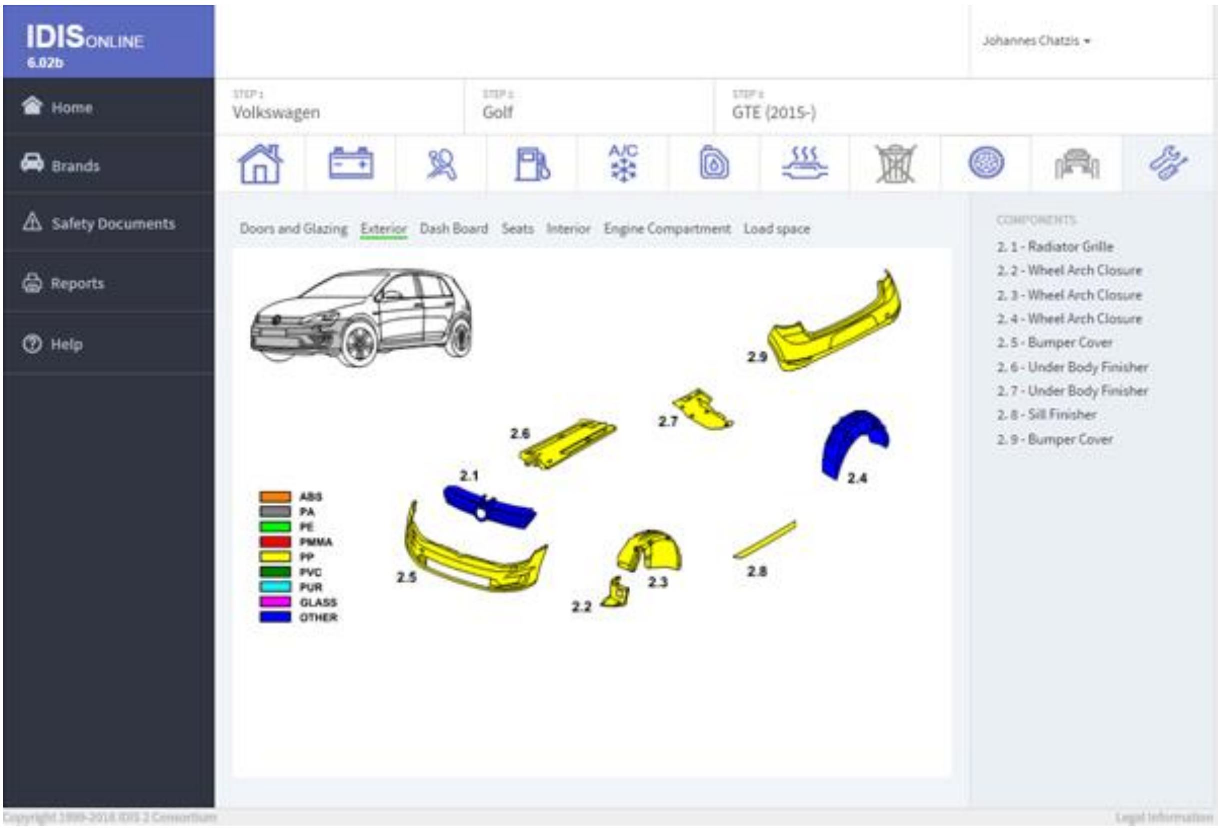
The IDIS software consists of two modules:

IDIS PLANT IS FOR VEHICLE DISMANTLERS. This module contains essential information filtered by materials, or parts of the vehicle. It also consults specific manuals and provides information on disassembly times. IDIS Plant enables the user to define groups of materials which will be stocked in the same bin during the recycling process. It will also be able to add a criterion about the weight of the part in addition to criteria about materials.

IDIS OFFICE IS FOR CAR MANUFACTURERS. This module includes functions enabling the management of brands and models, of parts and links between schematics and technical data, and of glossaries (name of the parts, tools, fixings, etc) in eight languages.

IDIS is the advanced and comprehensive information system for pre-treatment and dismantling information for End-of-Life Vehicles (ELV).

AREA DISMANTLING: Additionally to the pre-treatment information the material composition of potentially recyclable parts is given in colored pictures. The dismantling area is organized in sub areas like doors and glazing, engine room, dashboard. An exemple from IDIS guided tour is shown in 1-14. Figure.



1-14. Figure_ Example from IDIS-Area Dismantling
[https://www.idis2.com/discover.php]

IDIS contains safe handling information with focus on airbag deployment instructions, handling and treatment of high voltage batteries as well as gas vehicles.

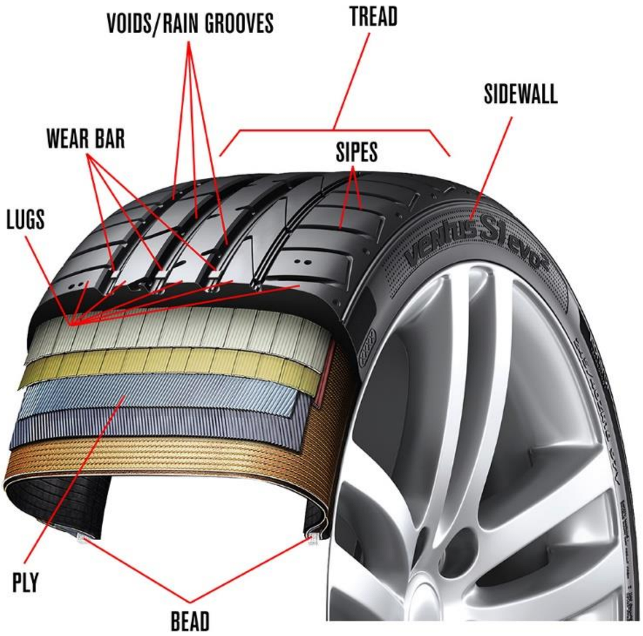
Organization of Data / IDIS Treatment Areas

To assure a safe, easy and fast access to the available data, all vehicle data is organized in different areas. These areas are: Batteries; Pyrotechnics; Fuels; AC; Draining; Catalysts; Controlled parts to be removed; Tyres; Other Pre-Treatment; Dismantling.
IDIS provides a user friendly navigation to an extensive database with practical information on pre-treatment, safety related issues like airbag deployment and handling of HV batteries, on potentially recyclable parts and other safety related elements mentioned in the EU ELV directive (e.g. lead in batteries or mercury and lead in electronic devices).
It is available as an online system for desktop and mobile tablet devices with continuous updates or as an offline version produced and updated once per year. In order to meet the "six months period" the offline version also provides access to IDISonline. Both systems are free of charge for all commercial end of life vehicle treatment operators in all countries covered by IDIS.

2 ADVANCED RECOVERY AND REUSE OF USED TIRES

Rubber, an energy-intensive material, is subject to wear and tear, no matter where it is used: for tires, elastic bands, tubes, gaskets, etc. Reusable rubber materials that are included in the collection obligations of businesses and the general public are generally worn or broken tires and inner tubes. Reusable materials from the industrial waste of the manufacturing units of rubber products, objects and articles have the character of circulating materials for which there are closed-circuit recovery regulations. The largest quantitative contribution to the source of recyclable rubber waste is used tires [16].

2.1 THE COMPONENTS OF A MODERN TIRE



2-1. Figure_ Tyre structure

[https://www.twt.co.za/tyre-top-tips/the-anatomy-of-the-tyre/]

TREAD - The tread is the part of the tyre that comes in contact with the road surface. The tread is made of thick rubber or rubber/composite compound with a pattern of grooves, lugs, voids and sipes. Every tyre comes with a different tread pattern, unique to that tyre.

RAIN GROOVES - These are needed to channel water away to help prevent aquaplaning.

LUGS are the portion of the tread that make contact with the road.

VOIDS are spaces between lugs that allow the lugs to flex and flush out water.

SIPES are valleys across the whole tyre. They run perpendicular to the grooves and allow water from the grooves to escape to help prevent aquaplaning.

WEAR BAR - Also known as wear indicators; these raised features at the bottom of tread grooves indicate that a tyre has reached its wear limit. When the tread lugs are worn away enough that the wear bars connect, it's time to replace the tyre.

2.2 METHODS OF CAPITALIZING ON USED TIRES

2.2.1 RETREADING OF USED TIRES

Retreading of used tires is a method of reconditioning that allows to obtain comparable tires, from the point of view of quality, with the new ones.

Reconditioning by retreading is practiced worldwide in all developed countries; is capitalized by this method over 25 of tire production.

With a retreaded anvelop, it can travel, on average, a distance that it is half the turnover of a new one, but its price is about 3 times lower.

Retreading only replaces the outer tread, which represents about 1/3 of the amount of rubber embedded in the product.

Used tires are a problem for even the most sophisticated waste management systems. Being made of complex polymeric materials, with a large addition of various other products, the recovery of this added value in any form is highly energy consuming and also dangerous.

In 2-2. Figure are presented the recovery methods and applications along the ELT waste management hierarchy.

WASTE HIERARCHY	REUSE	RECYCLING		OTHER MATERIAL RECOVERY	RECOVERY HYBRID			ENERGY RECOVERY	DISPOSAL
ELT INPUT	**Whole tires**	Whole or Shredded tires	Rubber granulate	Whole or Shredded tires, Rubber granulate, Crumb rubber and Powder	Whole or Shredded tires	Whole or Shredded tires	Steel cords, Whole or Shredded tires	Textile, Whole or Shredded tires	**Whole tires**
MANAGEMENT METHODS	**Repairing Regrooving Retreading**	**Granulation and associated applications**	**Reclamation**	**Civil engineering**	**Pyrolysis and gasification**				**Landfill Incineration**
PRODUCTS (OUTPUT)		Granulate and powder	Reclaimed rubber	N/A	Oil, gas, carbon/char, steel			**Other energy recovery**	
APPLICATIONS		▪ Artificial turf infill ▪ Athletics tracks ▪ Molded rubber products ▪ Playgrounds ▪ Roofing material ▪ Rubber-modified asphalt	▪ Inner tubes ▪ Insulation tiles used in public transportation for reducing the noise level ▪ Tiles for laying pedestrian concrete areas ▪ Tubeless tire liners	▪ Agricultural use ▪ Baled tires ▪ Breakwaters ▪ Coastal protection ▪ Erosion barriers ▪ Ground improvement ▪ Landfill construction operations ▪ Road embankments ▪ Shelters ▪ Slope stabilization ▪ Sound barriers, insulation applications	Carbon black: industrial gaseous effluents treatment (e.g. mercury, suplhur dioxide) Char: water and purification Oil and gas: TDF	**Cement Kilns**	**Steel production**	Alternative or additional fuel for energy generation in: ▪ Brick production ▪ Industrial boilers ▪ Power plants ▪ Pulp and paper mills ▪ Waste-to-energy plants	
EXAMPLES OF ADVANCED TECHNOLOGIES		▪ Absorption of phenol and oil in water ▪ Composites ▪ Concrete ▪ Micronized rubber powder ▪ Porous pipes from recycled ELT	Reclamation by depolymerisation by nitrous oxide	▪ Retaining walls ▪ Soft clay reinforcement	Use as anodes in lithium, potassium and sodium-ion batteries	N/A	N/A	N/A	

**The waste hierarchy category "Reduce" is not in the scope of this analysis. In addition, "Reuse" has been included, however this is not applicable to all tires and would depend on the condition of the product in relation to the appropriate safety standards.*

2-2. Figure_Position of recovery methods and applications along the ELT waste management hierarchy [https://docs.wbcsd.org/2019/12/Global_ELT_Management%E2%80%93A_global_state_of_knowledge_on_regulation_management_systems_impacts_of_recovery_and_technologies.pdf]

2.3 RECOVERY OF RUBBER FROM ELT

Recovery of rubber from non-separable used tires (by grinding at ambient temperature), as secondary raw material in powder form, for use as rubber additives in technical rubber articles, carpets, footwear.

Used tire recycling mainly refers to the mechanical grinding of tires, the separation of steel and the recycling of rubber itself.

The rubber is processed until granules are obtained that can be reused or further processed by mechanical and cryogenic grinding methods. Following the mechanical processing of the tires, rubber granules, steel elements, etc. are obtained. Important is the raw material for the production of other rubber products (eg car mats or rubber wheels for strollers, containers), but also the basic material for artificial turf.

A modern recycling line includes grinding machines, grinding mills, steel and textile sorting facilities and a line for sorting granular fractions of various sizes from 1 mm to 4 mm [17].

The Beston recycling plant (2-3. Figure) converts used tires into fuel oil through the pyrolysis process [18].

2-3. Figure_The Beston recycling plant

[https://bestoncompany.com/tyre-shredder/]

2.4 TURNS OLD TYRES AND OTHER RUBBER WASTE INTO MICRONIZED RUBBER POWDER

Lehigh Technologies Atlanta firm turns old tyres and other rubber waste into something called micronized rubber powder, which can then be used in a wide variety of applications from tyres to plastics, asphalt and construction material. Five hundred million new tyres have been made using its products, earning it the Award for Circular Economy SME [19].

2-4. Figure_ LeHigh Technologies

[https://www.lehightechnologies.com/]

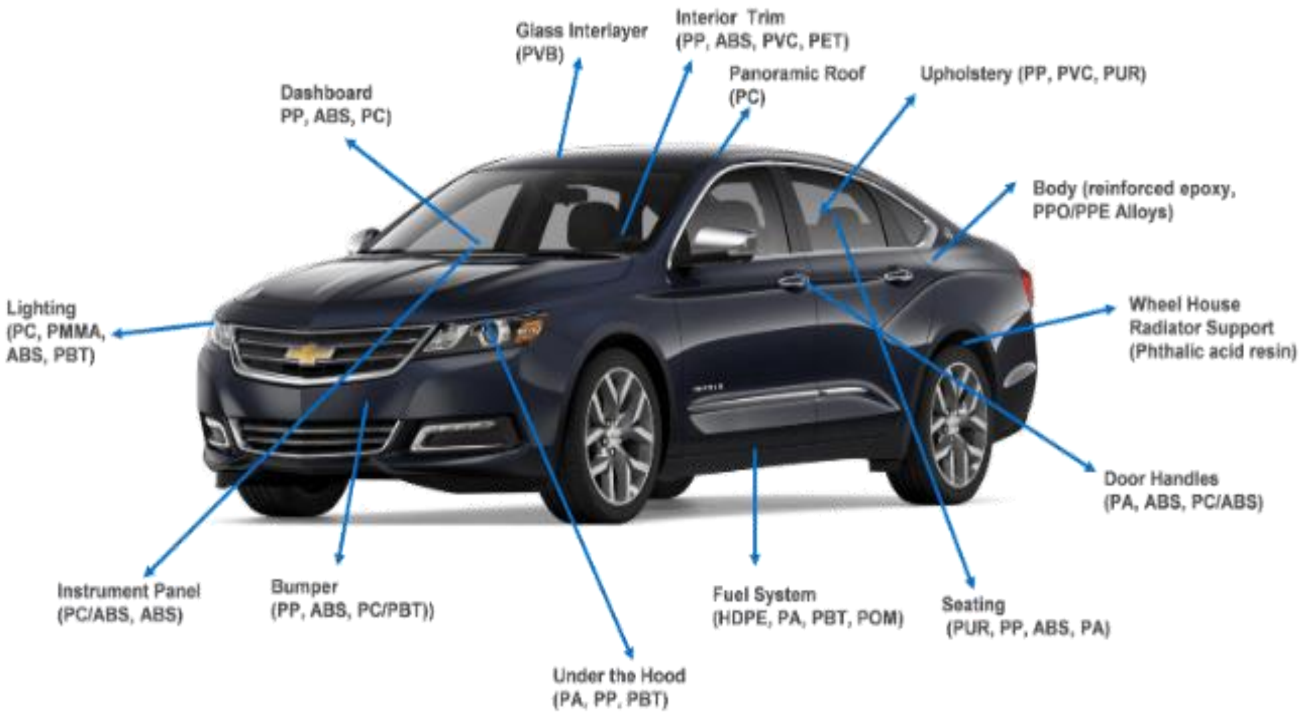
3 PLASTIC WASTE RECOVERY

3.1 PLASTICS APPLICATIONS IN AUTOMOTIVE PARTS

The role of plastic in the design and manufacturing of automotive vehicles has become essential, with strict regulations driving demand for more affordable, lightweight, and fuel-efficient vehicles.

Currently, there are about 30,000 parts in a vehicle, out of which 1/3 are made of plastic. In total, about 39 different types of basic plastics and polymers are used to make an automobile. More than 70% of the plastic used in automobiles comes from four polymers: polypropylene, polyurethane, polyamides and PVC.

Plastic has become one of the key materials required for the structure, performance, and safety of automobiles in recent years, with growth in plastic consumption being driven by light weighting trends for fuel efficiency and consequently lower greenhouse gas emissions. The high absorption properties of plastics also allow the vehicle to meet stricter safety standards, while the use of engineering plastics allows for minimization of the mass of parts used in vehicles as they offer more design freedom compared to metals [20].



3-1. Figure_ Plastics applications in automotive parts [http://adapt.mx/plastics-in-the-automotive-industry-which-materials-will-be-the-winners-and-losers/]

Table 3.1 Common plastics used in a typical car

Component	Types of Polymers
Bumpers and fascia systems	PS, ABS, PC/PBT, PP, PA, PU, TPO
Seating	ABS, PA, PP
Instrument panels	ABS, PC, ABS/PC, PP
Fuel systems	POM, PA, PBT
Under hood components	PA, PBT
Interior trim	ABS, PET, POM
Electrical components	PBT, PA
Exterior trim	PS, PVC, ABS, PA, PBT, POM, ASA
Lighting systems	PC, PBT, ABS, PMMA
Upholstery	ABS, PU
Liquid reservoirs, cooling, battery carriers	PA
Wheel covers	ABS
Body parts	ABS
Tires	PA
Parts of engine	PA, phenolic resins

ABS (acryl butadiene styrene), ASA (acrylonitrile styrene acrylate), PA (polyamide), PBT (polybutylene terephthalate), PC (polycarbonate), PET (polyethylene terephthalate), PMMA (polymethyl methacrylate), POM (polyoxymethylene), PP (polypropylene), PS (polystyrene), PU (polyurethane), TPO (thermoplastic polyolefins).

Engineering and conventional plastics, also termed fossil-derived plastics, are not biodegradable by microorganisms within a reasonable time frame. Generally, it would take about 300 years for 60 mm of some plastic films to degrade entirely in soil; this is why plastics are considered an ecological problem [21].

A great amount of the plastic waste components are still treated as “waste,” and there is a significant opportunity to recycle more of the plastics used in the automotive sector.

Factors that currently limit mechanical recycling include: contamination issues, technical challenges of separating resins in mixed resin products, and lack of markets for some plastics.

While technically all thermoplastics can be recycled, the conditions identified above can make recovery through mechanical recycling economically impossible. The result is that many plastics still are not recovered at end-of-life.

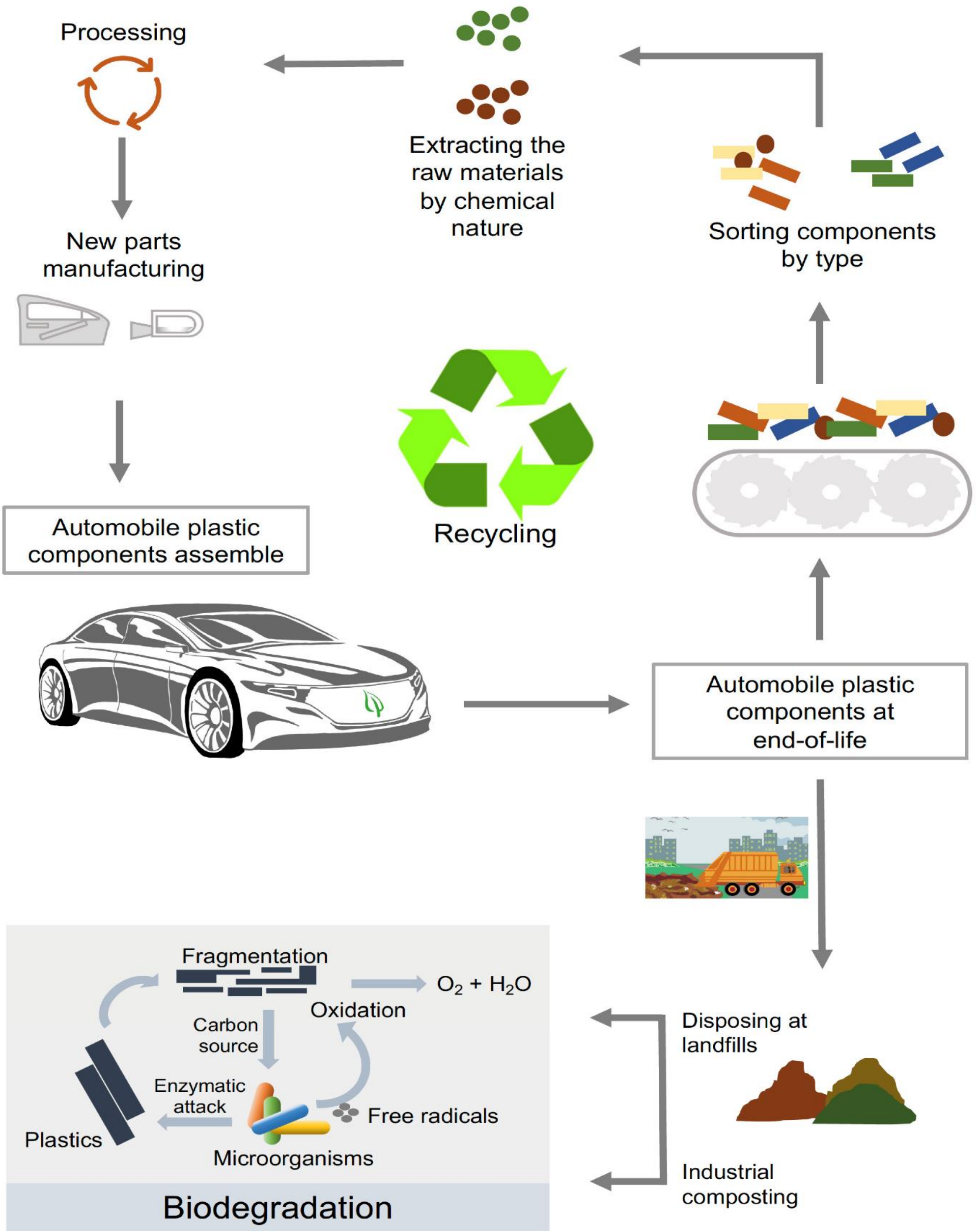


Figure 3-2 Automobile bioplastic components disposal at end-of-life [https://doi.org/10.3390/polym14163412]

Some plastic parts can be recycled, enabling the manufacturer to reuse materials cost-effectively. A plastic disposal program should include one branch of recycling and one of disposing of biodegradable plastics. [22]

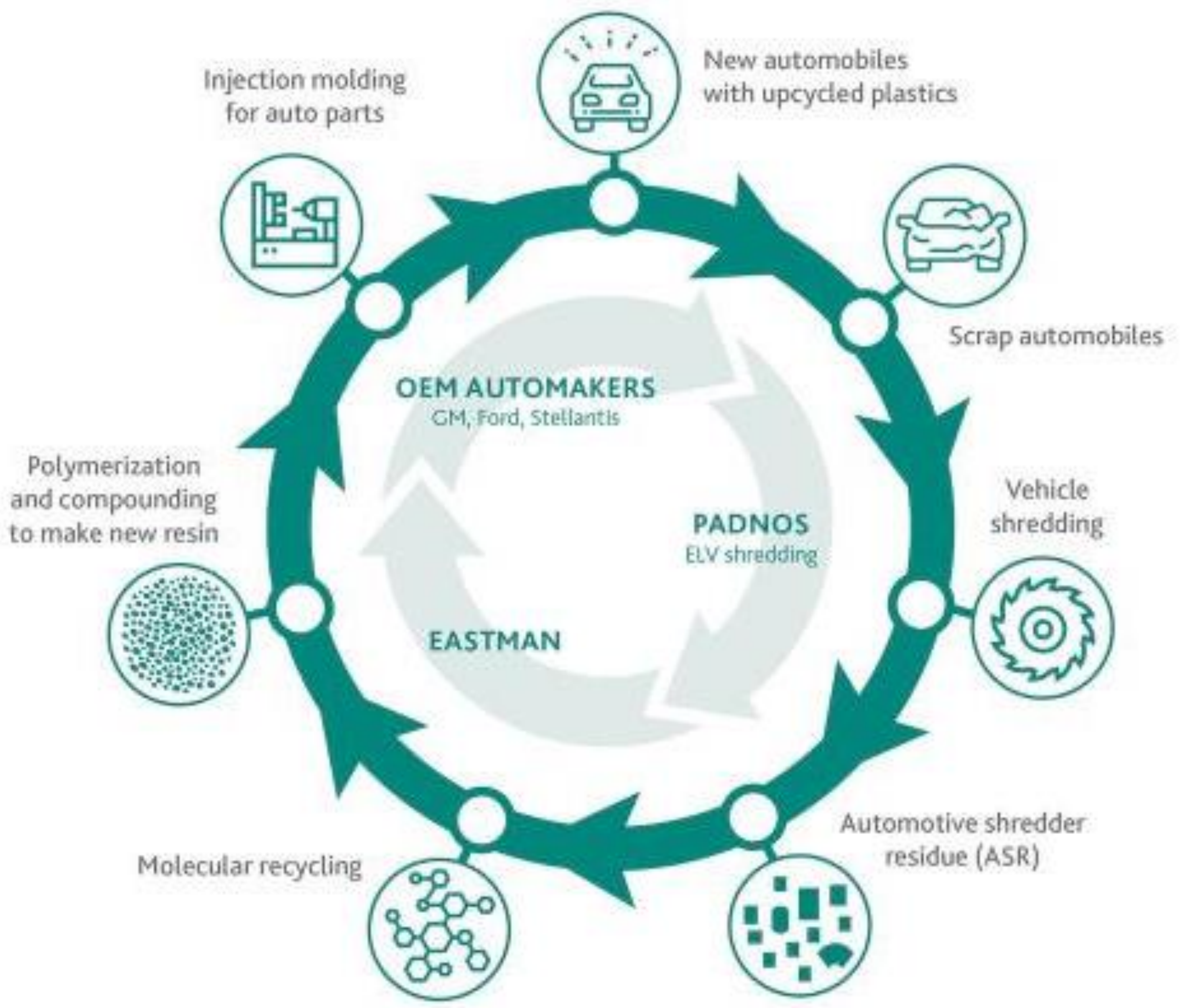
Some recycled plastics are in use in the automotive industry.

- ☑ The Karlsruhe Institute of Technology (KIT) and Audi launched a pilot project for recycling plastics in 2020. The no-longer-needed plastic parts, such as fuel tanks, decorative wheel trims, or radiator grilles from Audi models, are turned into pyrolysis oil through chemical recycling. The quality of this oil equals that of petroleum products, with the materials made from it offering the same high quality as new goods. The objective is to create new automobile parts from this pyrolysis oil.
- ☑ Ford announced progress towards using 20% renewable and recycled plastics by 2025.
- ☑ In their 2030 milestone program, Toyota envisions establishing 30 plants for the appropriate treatment and recycling end-of-life vehicles.

Overall, the estimated costs, efficiencies, and environmental impact are critical factors when recycling plastics in the automotive industry. Some of the typical plastics used in the industry are relatively cheap to recycle, but they may have a high impact on the environment regarding the carbon footprint. The plastics that release high amounts of CO_2 into the environment are unsuitable for recycling. Additionally, the actual fractions of recycled plastic incorporated into the supply chain (efficiency) depend highly on the material class. For example, ABS is easy to recycle, suitable for general use, and highly efficiently recycled

3.2 INNOVATIVE PLASTIC RECYCLING USING A BY-PRODUCT OF SHREDDED END-OF-LIFE VEHICLES

Eastman has announced the successful completion of its closed-loop recycling project for automotive mixed plastic waste. Through a collaborative effort, Eastman, the United States Automotive Materials Partnership LLC (USAMP), automotive recycler Padnos, and global automotive interior supplier Yanfeng demonstrated first-of-its-kind plastic recycling using a by-product of shredded end-of-life vehicles [[23]].



3-3. Figure_Closed-loop recycling of automotive mixed plastic waste

[https://www.plasticstoday.com/automotive-and-mobility/closed-loop-recycling-automotive-mixed-plastic-waste-deemed-success]

TECHNOLOGY DIVERTS PLASTIC WASTE FROM LANDFILL

When automobiles are at the end of their life, metals, tires, and glass account for 80 to 90% of the materials that can be recycled through traditional mechanical recycling streams. The other 10 to 20%, referred to as automotive shredder residue (ASR), consist of mixed plastic and other nonrecycled materials that currently end up in landfills or are recovered through waste-to-energy technologies.

Under this initiative, Padnos supplied a plastic-rich fraction of ASR as a sustainable feedstock to Eastman's carbon renewal technology. Eastman successfully demonstrated addition and conversion of that ASR feedstock into a synthesis gas (syngas), which is subsequently used downstream in the production of its polyester and cellulosic thermoplastics. Resins from this production process were further formulated and then supplied to Yanfeng. The parts molded by Yanfeng for demonstration were successfully tested to meet a variety of OEM – Ford, GM, and Stellantis – requirements, thereby demonstrating proof of concept for a truly circular solution.

PROVEN FEASIBILITY OF MOLECULAR RECYCLING

The study proved feasibility of Eastman's carbon renewal technology (CRT), one of Eastman's two molecular recycling technologies, which breaks down the plastic-rich ASR into molecular building blocks. By recycling these complex plastics in CRT, Eastman can replace fossil-based feedstock and create polymers without compromising performance for use in new automotive applications.

In addition to diverting waste from landfills, USAMP, a subsidiary of the United States Council for Automotive Research LLC (USCAR), also sees the potential for energy savings and reduced overall greenhouse gas emissions.

Deloitte Consulting estimates that more than 10 billion pounds (4.5 million toones) of ASR is sent to landfills globally each year.

3.3 WIPAG – OPEN LOOP AND CLOSED LOOP RECYCLING

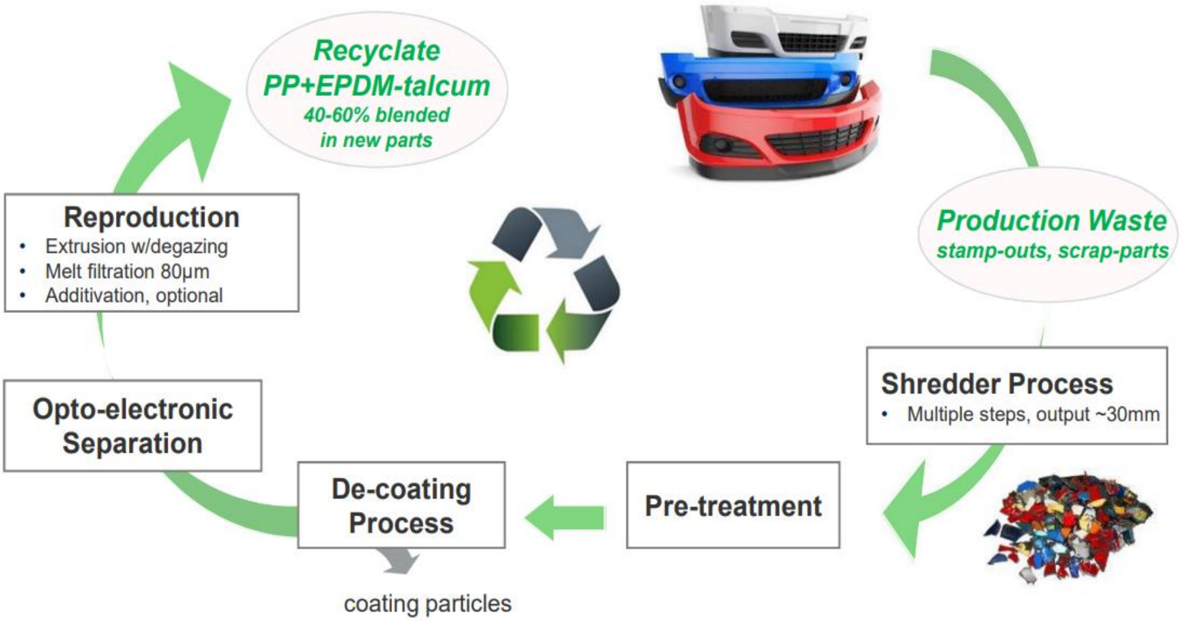
WIPAG recycles post-industrial and post-consumer plastic waste from several industries with its main focus on automotive parts. Recycled parts comprise bumpers, dashboards, wheel-arch-liners, rocker-panel, front-ends, etc. [[24]]. Production residues such as stamp-outs and scrap parts (post-industrial) or parts from end-of-life vehicles (post-consumer) go through a complex recycling process including shredding, delamination, density separation and electrostatic separation [[25]].

WIPAG initiates material cycles:

Using **OPEN-LOOP AND CLOSED-LOOP TECHNOLOGIES**, it produces a wide portfolio of recycled compounds of various grades and high-tech carbon fiber compounds for customers.

This means that old plastics do not end up in landfills, but are returned to the value creation cycle. The use of new materials can be reduced – in some cases even completely replaced.

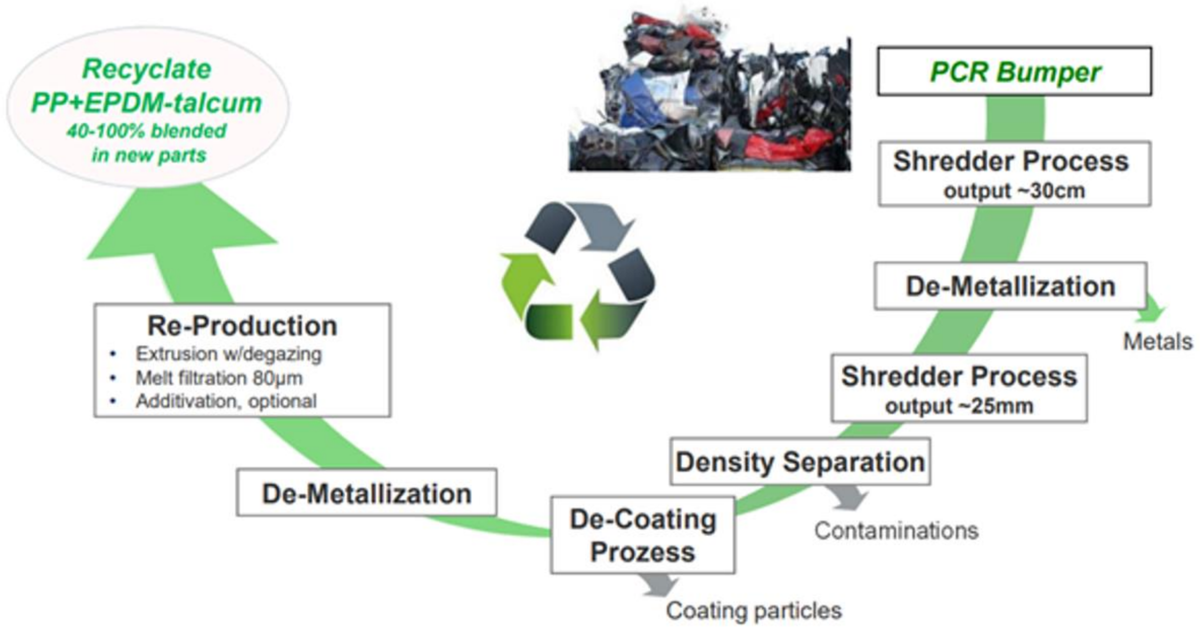
WIPAG – CLOSED LOOP RECYCLING VALUE CHAIN >> BUMPER TO BUMPER (PIR)



3-4. Figure_ WIPAG – Closed loop recycling value chain >> bumper to bumper (PIR)

[Source: https://circulareconomy.europa.eu/platform/sites/default/files/bsp_albis_wipag_open_loop_closed_loop_raas_10_19s.pdf]

WIPAG – CLOSED LOOP RECYCLING VALUE CHAIN >> BUMPER TO BUMPER (PCR)



3-5. Figure_ WIPAG – Closed loop recycling value chain >> bumper to bumper (PCR)

[Source: https://circulareconomy.europa.eu/platform/sites/default/files/bsp_albis_wipag_open_loop_closed_loop_raas_10_19s.pdf]

End products are Wipalen PP-GF compound or Wipelast PP-EPDM TV20 compound for the production of new automotive parts.

Wipalen can be included in new production up to 35%; from 40 to 100% of total amount.

While automotive plastic parts recycling proves efficient in terms of industrial results, the business considers stringent specification regimes at OEM/Tier1 level and sometimes cost pressure from low priced prime polymers, as a challenge for recycling momentum in automotive and other industries.

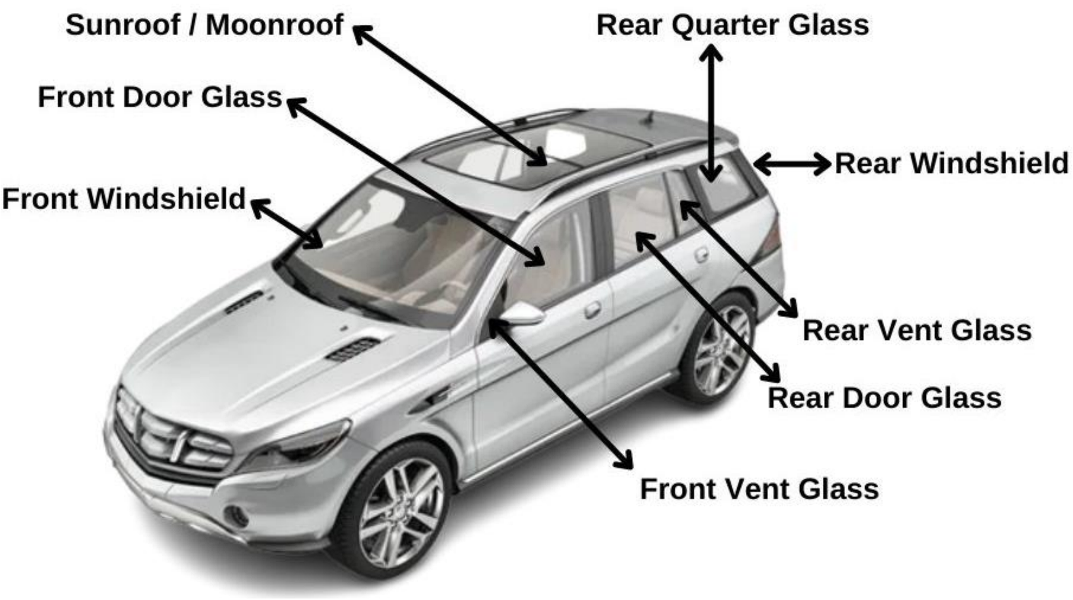
The benefits are obvious: lower raw material acquisition costs and more durable plastics that help reduce the CO2 balance and reduce the ecological footprint, while maintaining a high standard of quality.

4 ADVANCED TECHNOLOGIES FOR RECOVERY OF GLASS WASTE FROM THE AUTOMOTIVE INDUSTRY

4.1 AUTOMOTIVE GLASS RECYCLING CHALLENGES

The automotive glass consist of different glass parts such as windshields or windscreens, sidelights (windows for front and back door), backlights (rear window), quarter lights (back window next to rear door window), and sunroofs. Automotive glass accounts for approximately 3% of a vehicle by mass and presents unique challenges for manufacturing and recycling. Companies are finding ways to overcome these challenges and reduce the environmental impact of this multi-billion dollar industry.

The flat glass used in windscreens, side windows, backlights, panoramic sunroofs and mirrors is an essential part of a vehicle. It is designed so that if it breaks, no dangerous sharp shards will result. It is meant to guarantee unaltered visibility to drivers and safety to vehicle occupants in case of accident while being an essential part of a vehicle design and a substrate for the integration of sensors, cameras and lidar, enabling assisted and automated driving. Auto glass is also designed to withstand the force of wind from high-speed driving, the impact of road debris, and also support the structure of the cabin during collisions. The common auto glass parts are shown in *4-1. Figure*.



4-1. Figure_ Auto glass parts
[https://www.glassfixitauto.com/blog/auto-glass-parts/]

The automotive glass have specific options and are made with different glass techniques such as windscreens with rain sensor, tinted glass or athermic glass; tempered front door sidelights; laminated front door sidelights; tempered rear door sidelights; laminated rear door sidelights; and fixed backlights [26].

By adjusting the composition and structure of auto glass, manufacturers produce a robust safety material that gives drivers and passengers a clear view of their surroundings while controlling cabin temperature and acoustics, as well as vehicle weight and energy efficiency.

But this complex structure makes the material difficult to recycle compared to other types of glass.

Windshield Glass vs Rear Windshield/ Back Glass:

The windshield is located in front and is one of the vehicle's most significant components. The rear windshield (or rear glass) is located at the back of the vehicle and is similar to the front windshield in that it helps maintain the rigidity of the vehicle's frame as well as protects its occupants.

Besides its structure, operation, and function, rear windshield is distinguished from the front windshield.

⇨ They Both Perform Different Functions

Determining the visibility and frame: The front windshield provides well-defined visibility to the driver (and other passengers) of the vehicle. There are wipers fit into the glass that can be operated to clean the glass, removing dust, rainwater, etc. Also, the front windshield makes the frame of the car more prominent.

The rear windshield makes the car safer. There is a glass guard at the back side of the vehicle and the possibility of theft decreases.

⇨ Different Types of Glasses are used during manufacturing

A major difference between the front and rear windshields is the type of glass used in their manufacturing process. The characteristics of the glasses used to manufacture the windshields differ according to their functional features.

Laminated glasses are used to manufacture the front windshield. Laminated glass is made by fusing a thin layer of polyvinyl butyral (PVB) with two solid glass layers. The three layers are subjected to extreme heat and pressure to form a strong, rigid glass product. It is resistant to minor pressure. Also, it protects the passengers against hurled things. In almost every case, the front windshield has higher safety standards compared to the rear windshield.

When a front windshield break or is punctured, it stays intact instead of shattering, as is the case with ordinary glass because it's bonded with PVB. Windshield deflect up to 95% of the harmful UV rays emitted by the sun to keep drivers safe and allows for the safe deployment of the passenger airbag. This airbag bounces off the windshield at incredible speed and force before heading towards the passenger.

Laminated safety glass is more complex to get recycle-ready, since the plastic sheet needs to be removed prior to recycling.

The rear windshields are mainly manufactured from high-quality tempered glass. Tempered glass is made by heating glass and then rapidly cooling it to room temperature to increase its tensile and compressive strength. Tempered glass is 5 to 10 times stronger than ordinary glass. The high tensile and compressive strength of tempered glass ensures that car windows don't break when drive over a pothole, get into a fender bender, or bang the car doors. When the glass gets broken due to an external (or internal) impact, it doesn't get shattered into shards. It breaks into smaller fragments and tiny parts due to the impact.

4-2. Figure_ Tempered glass vs Laminated glass

a)Tempered glass: Shatters completely under higher levels of impact energy, and few pieces remain in the frame; b) Laminated glass: May crack under pressure, but tends to remain integral, adhering to the plastic vinyl interlayer

[https://destinglass.com/annealed-vs-tempered-vs-laminated-glass-differences/]

The Presence of a Defrost Grid

In most cases, the rear windshields of cars have a defrost grid. It is an essential component that helps in getting rid of frost in cold winter mornings. The attribute is inherent to the rear windshield of the car and automatically keeps the rear glass clean.

On the other hand, the front windshield of a car doesn't have any such defrost grid.

Front and Rear Door Glasses:

The side glass panes are located on the sides of the vehicle in the doors. Side windows can be of many shapes and sizes, and either sliding or stationary. An electric motor on modern automobiles operates the window glass up and down, and the passengers control the function.

Vent Glass: Vent windows are an important part of vehicle design, blending function and form. Although vehicles are becoming more sophisticated with new technologies and are losing their vent windows, side windows have been a standard and a complement for many vehicle generations.

Quarter Glass: is just as important as the retractable side windows and the rear windshield, both of which are made of the same tempered or laminated glass to prevent harm. Quarter glass is used to see the surrounding area because it is made of the same tempered or laminated glass as the side windows and rear windshield, which are designed to shatter into tiny glass balls.

Sunroof/ Moonroof glass:

The vehicle's roof provides both fresh air and light to the vehicle's passenger compartment via the auto glass. An opaque or transparent sunroof with a visor that blocks light from the passenger compartment can be opened in one of two ways: the sunroof vents when it is fixed open, or the sunroof slides and retracts either onto the roof or under the interior headliner when it is operable.

Side and rear windows are generally made of **tempered glass**, which is stronger than ordinary glass. Tempered glass provides enhanced safety as it fractures into small, relatively harmless pieces when it breaks. This type of glass is 'purer' as there is no plastic laminate to remove, however its collection is more difficult as it can shatter in small fragments during its dismantling from the car.

In modern vehicles, glazing is bonded to the body of the vehicle for safety reasons. In practice, it is generally glued, which makes it harder to remove.

Automotive glazing parts increasingly **integrate other materials than glass to fulfil extra functions**.

Glass pieces may include plastic interlayers for laminated safety and acoustics, ceramic inks for design, silver printing electrical connectors and sensors, encapsulation materials, fixing clips, etc., according to the vehicle manufacturer's demands. In electric or hybrid cars, glass sunroofs can also integrate solar PV modules. This complexity of automotive glass pieces requested by OEMs implies that, once the automotive glass piece is dismantled from the vehicle, a thorough sorting of materials is necessary.

Integrating automotive glass into the circular economy concept requires OEMs to improve vehicle design to make automotive glass "dismantling ready" and to adopt a "designed for recycling" approach, prior to the procurement of glass components.

4.1.1 RECOVERY AND RECYCLING OF FLAT GLASS

The **removal of the glass pieces from the vehicle** is the first essential step. It requires preserving vehicle's integrity. Half of the end-of-life vehicles reach dismantlers without windows or with destroyed windows, making for a very low recycling potential. When removal is undertaken, it requires several minutes of manual work because fixed glazing is bonded to the vehicle body [[27]].

Once removed from the vehicle, **glass needs to be sorted** by type, i.e. laminated, tempered, silver printed rear windows, etc. This separation must be with an adequate size, purity and colour sorting system, to avoid contamination. The average time for this operation is of the order of 30-40 minutes per vehicle and involves a cost of approximately €1,000 per tonne, so the decision regarding the treatment of end-of-life vehicles lies in the hands of dismantlers (Authorised Treatment Facilities, ATFs) which balance time, costs and benefits. Currently, most of the glass in end-of-life vehicles is not recovered [27].

Finally, collected glass pieces require **treatment to ensure the removal of all potential contaminants**, such as plastic interlayers from laminated glass. Automotive glass products necessitate the highest quality and purity to ensure unaltered visibility and safety. Contaminants in raw materials and cullet generate production defects but can also jeopardise the glazing structure and cause serious damage to the industrial equipment. For these reasons, **the flat glass industry has the most stringent quality specifications for sourcing cullet [27]**.

Because quality specifications for recycled glass are not as strict in other glass sectors as in the flat glass sector, for instance in container glass or glass fibre, for which visibility and transparency are not essential selling points, some flat glass cullet of automotive origin may be used by these glass sectors at a lower quality level and cost than what could be possible in flat glass manufacturing.

Most windshields are made from laminated glass. Laminated glass is manufactured by sealing two layers of glass together with a polyvinyl butyral (PVB) interlayer. The PVB interlayer is what helps the windshield to stay intact in the event of an accident and helps provide important structural support to your vehicle's roof.

When windshields are recycled PVB must be separated from the glass. In most cases, the used windshields are first pulverized or crushed. After that, a machine separates the glass from the PVB. The glass is processed into something called "glass cullet," which can be used in a variety of applications, such as concrete, fiberglass insulation, asphalt and more. The PVB also can be used for various adhesive applications [[28]].

Because this process is so difficult, many auto glass companies have entered into agreements with laminated recyclers to recycle windshields and subcontract their recycling after replacing the windshields.

The same features that make windshields tough and safe also make them difficult to recycle. By design, the glass is tightly bonded to the rubbery sheet of PVB and adheres strongly even after the glass breaks.

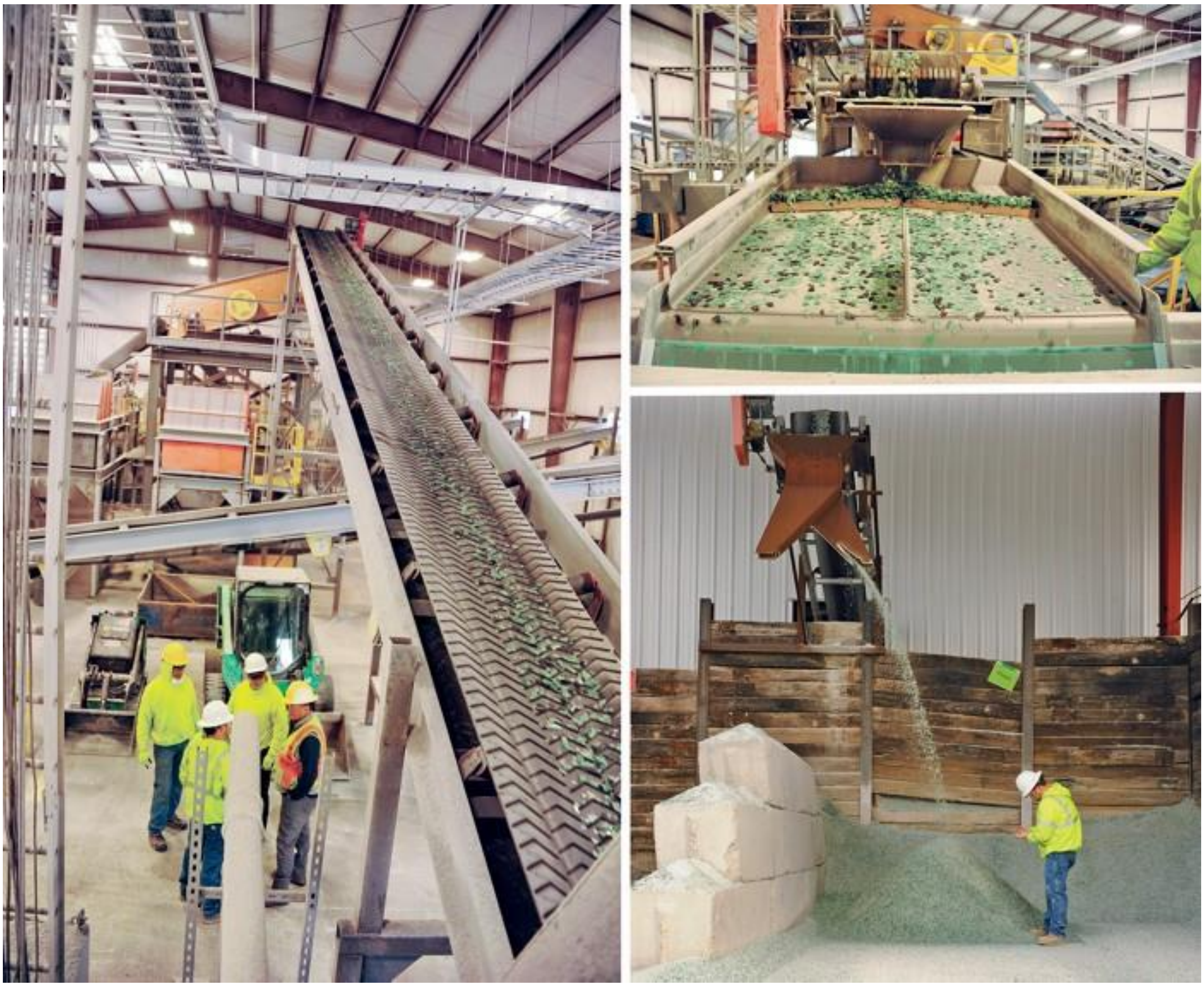
So even though glass recyclers process many millions of metric tons of container glass annually, they have traditionally recycled very few windshields.

Utilizing the high-quality characteristics of automotive glass, powdered glass from shredder residue is recycled into tiles with remarkable density and strength, and also used as materials for landscaping pavement.

The European flat glass industry is eager to collect and use more flat glass waste, aka 'cullet', in its manufacturing process to decrease the use of virgin raw materials and reduce CO2 emissions. End-of-life automotive glass pieces could be a new source of cullet if collection, sorting and quality can be improved.

4.2 CRUSHED AUTOMOBILE GLASS USED FOR MAKING NEW GLASS

At Strategic Materials in Moraine, Ohio, crushed automobile glass moves along conveyors (left) to various sorting machines (top, right), which generate mounds of clean cullet (bottom, right) used for making new glass [29].



4-3. Figure_ Crushed automobile glass recycling at Strategic Materials in Moraine, Ohio [https://cen.acs.org/materials/inorganic-chemistry/Automotive-glass-manufacturing-and-recycling-presents-unique-challenges/100/i14]

Andela Products is a company that has developed one way to pry the windshield materials apart. The method is based on a hammer-and-chisel-like approach. Equipment beats the windshield from both sides simultaneously—repeatedly and at high speed, fracturing the glass and mechanically peeling it from the PVB. The stripping process yields millimeter-sized cullet and larger pieces of PVB [[30],[31]].

4.3 WASTE WINDSHIELD-DERIVED SILICON/CARBON NANOCOMPOSITES AS HIGH-PERFORMANCE LITHIUM-ION BATTERY ANODES

Waste glass is mainly composed of amorphous silica (64%), which is a suitable silicon source. Waste glass is typically collected from various industrial wastes, such as windows, displays, bottles, and glass products. The collected waste glass is recycled for use as raw materials or manufactured goods.

Laminated glass from windshield end in landfill because of polyvinyl butyral (PVB) adhesive films between two glasses.

The waste PVB film leads to a laborious recycling process to separate the glass and PVB film. However, the organic PVB film can be an appropriate carbon source due to its 67.6% carbon content. In laminated glass derived from waste windshields, the glass and PVB film can be the silicon and the carbon precursors, respectively. This work represents the first synthesis of a silicon/carbon composite anode for LIBs using waste windshields as both silicon and carbon precursors.

3D silicon anodes was synthesized using glass from waste windshields via magnesiothermic reduction and acid-treatment. To further improve the electrochemical properties, silicon/carbon composites are fabricated using PVB films from windshields via a simple carbonization process. The silicon/carbon composite electrodes demonstrated high capacity and long cycle life due to their unique nanostructures and inclusion of conductive carbon.

The two-step process used to fabricate the silicon/carbon composites using waste windshield. During the synthesis processes, reduced Si (R-Si) and R-Si/carbon composites are obtained; these samples are named R-Si@PVBn (n = 40 or 100) depending on the PVB/R-Si weight ratio.

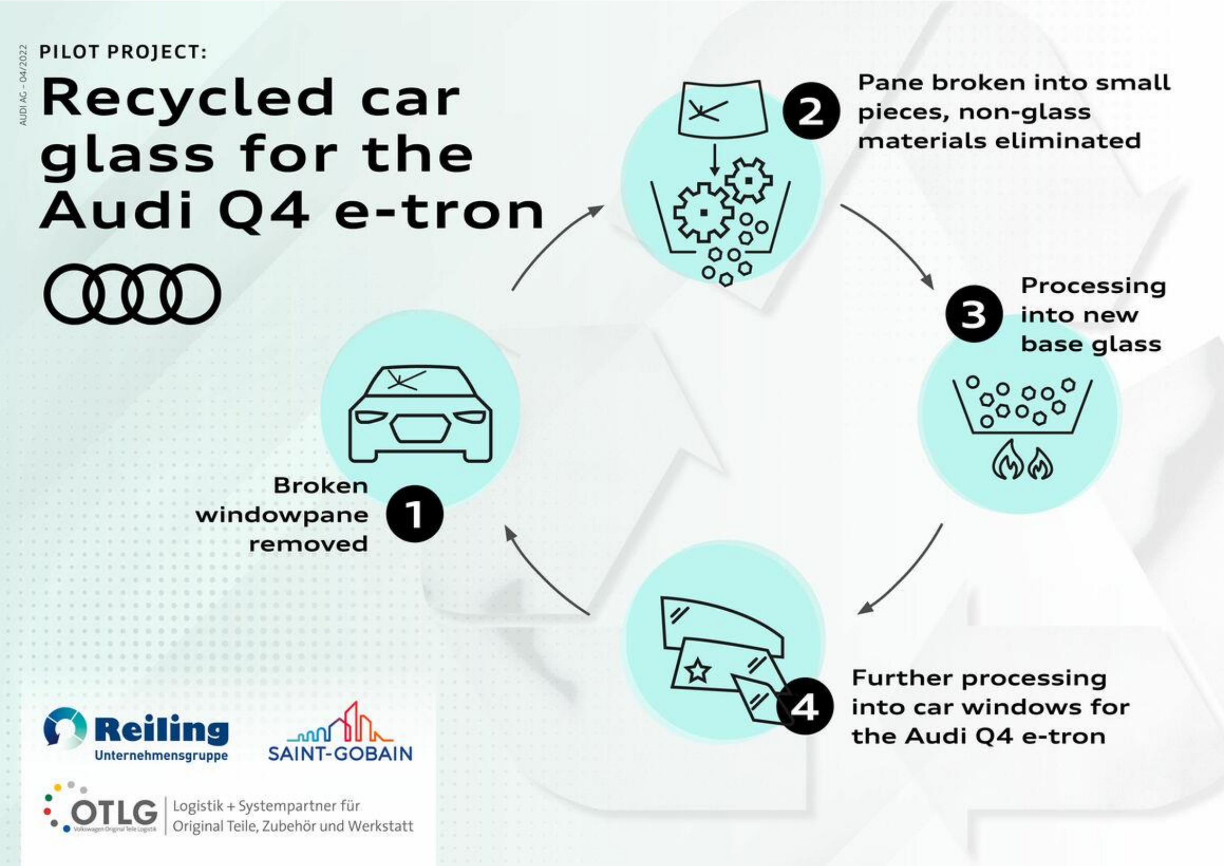
4-4. Figure_Schematic of the synthesis method of reduced silicon and silicon/carbon composites for lithium-ion batteries
[https://doi.org/10.1038/s41598-018-19529-1]

To obtain better cycling retention, R-Si/carbon composites were fabricated using waste PVB film as the carbon resource. The R-Si@PVB40 and R-Si@PVB100 electrodes exhibited excellent cycling retention, compared with the R-Si electrodes. This cost-effective fabrication method, which produces a high-performance silicon/carbon composite anode material, is advantageous for its various potential use in recycling industry of waste windshields [32].

4.4 AUDI GLASS-RECYCLING PILOT PROJECT

AUDI's goal is to manufacture the upholstery entirely from the same type of material so that it can be recycled. If its technical feasibility is proven, Audi plans to industrialize the technology in question and then progressively apply it to more and more components.

Broken car windows often go to recycling when they cannot be repaired, there is still no closed material loop for damaged car windows. Audi and its partner companies Reiling Glas Recycling, Saint-Gobain Glass and Saint-Gobain Sekurit are conducting a joint pilot project to turn damaged car glass into recyclable material for the production of new models. They developed a multi-step process for using an innovative recycling process: car windows are first broken into small pieces; all non-glass impurities such as glue residue are then removed; the resulting glass granules are melted down and turned into new glass. That sheet of glass is then turned into a new car window [33].



4-5. Figure_Recycled car glass for Audi Q4-E-TRON

[Source: https://www.audi-mediacenter.com/en/photos/detail/recycled-car-glass-for-the-audi-q4-e-tron-108899]

Audi is now shifting the “GlassLoop” pilot project into standard production; for the windshields in the Audi Q4 e-tron, the company will use glass made of up to 30% recycled material from car windows damaged beyond repair. Audi, in cooperation with its partner companies, is the first premium auto manufacturer to set up a glass cycle of this kind.

Until now, car windows damaged beyond repair—mainly windshields and panoramic roofs—have been used for less demanding purposes, such as bottles or insulation, in what is known as downcycling. The pilot project was the first to demonstrate that glass could be reused at comparable quality [34].

5 CIRCULAR ECONOMY - THE SECOND CHANCE AT LIFE OF EV BATTERIES

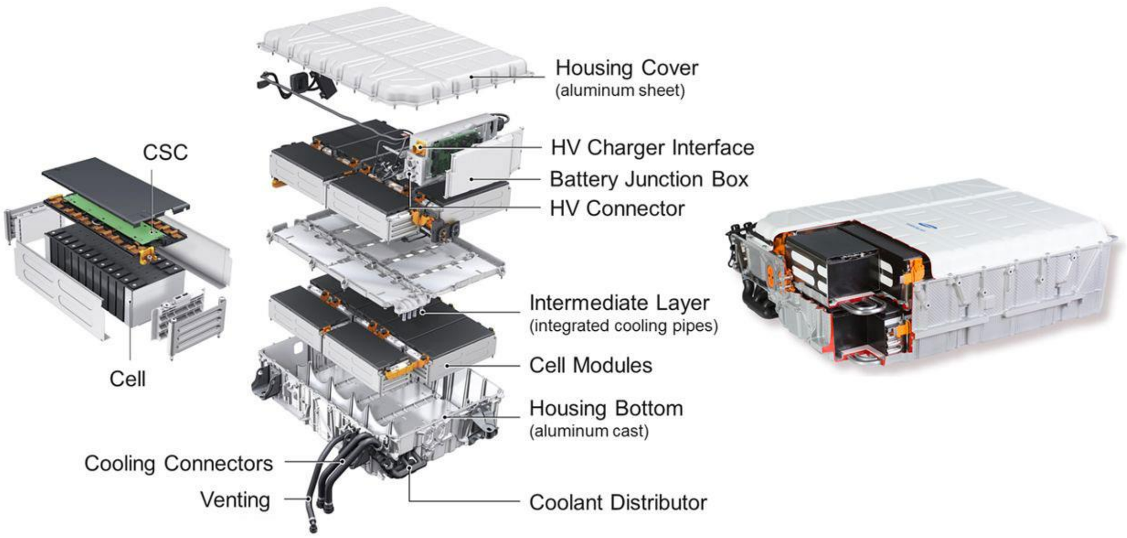
5.1 WASTE MANAGEMENT HIERARCHY FOR LIB

Advancements in lithium ion battery (LIB) technologies have increased the practicality and attractiveness of electrically-driven vehicles (EV), leading to an increase in their development and production, as well as that of LIV. Despite of this, the problem still remains to develop a truly sustainable method of dealing with these batteries at their end-of-life (EOL).

One possibility is to give EOL EV batteries a second life as stationary energy storage.

The term LIB covers a range of different battery chemistries, each with different performance attributes. LIBs are configured in cells, modules, and systems. Battery modules and especially systems need peripheral units such as a temperature and a battery management system.

Depending on the field of application, the design of cells and modules varies considerably. Whereas applications with a smaller battery size often use cylindrical cells due to their dimensions, prismatic cells are primarily used for bigger battery systems, e.g., traction batteries. Pouch cells with an Al composite foil as a casing instead of a rigid Al or steel casing are used among a wide range of applications in order to increase the energy density. In addition, battery systems without module levels are currently under development [35].

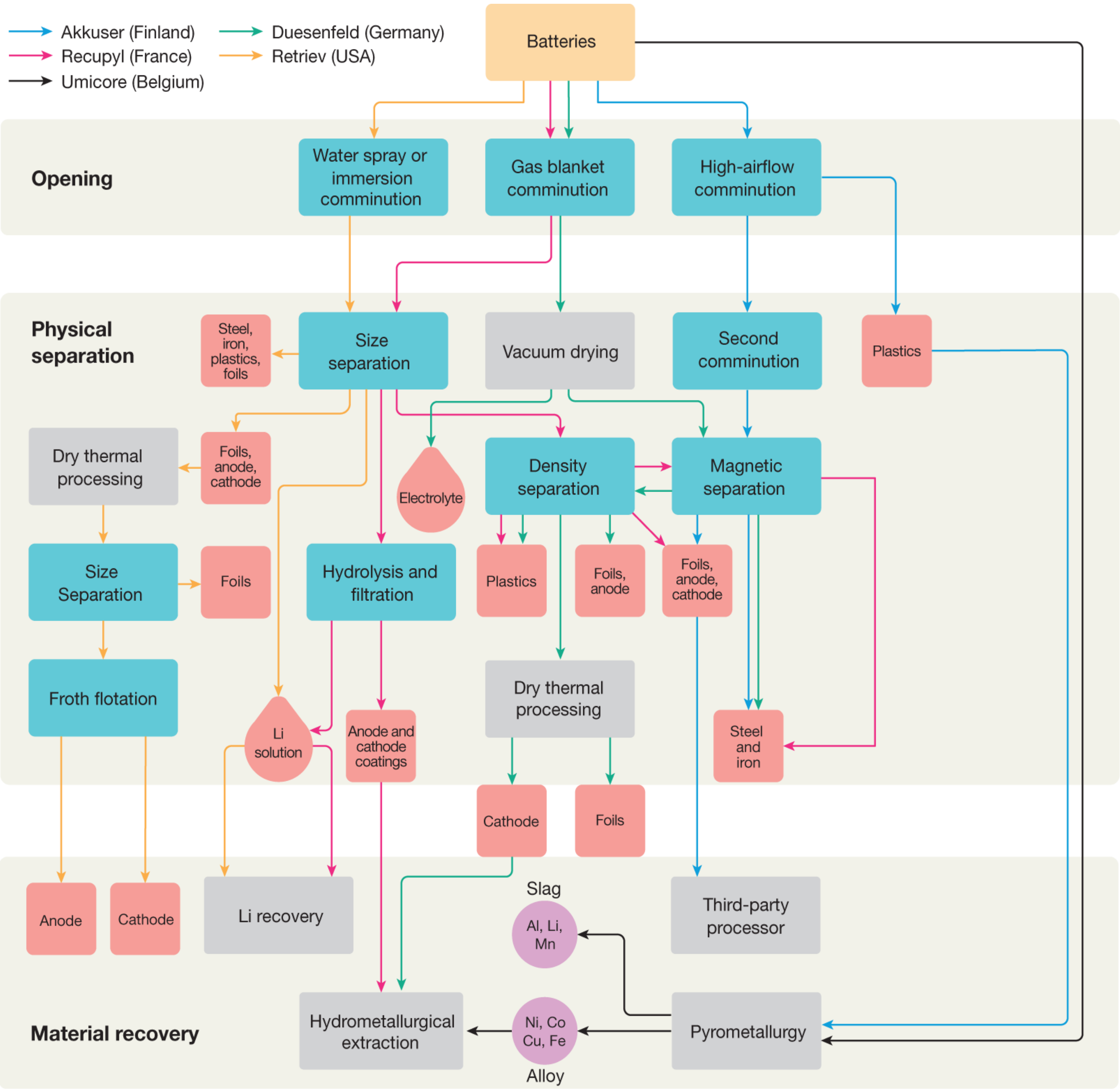


5-1. Figure_Schematic build-up of an automotive battery system

[Source: SAMSUNG SDI]

The basic concept of a LIB is that lithium can intercalate into and out of an open structure, which consists of either ‘layers’ or ‘tunnels’. Generally the anode is graphite but the cathode material may have different chemistries and structures, which result in different performance attributes and there are trade-offs and compromises with each technology. The cathode chemistries of LIBs have a large impact on the performance of LIBs, and these chemistries have evolved and improved [36].

The batteries of electric cars mostly receive a second chance at life after they no longer serve the purpose for which they were built, for example, are used in charging stations on highways or become energy generators for homes. The potential routes for the circular economy of LIBs are pointed out in *5-2. Figure*.



5-2. Figure_ Flow chart representing potential routes for the circular economy of LIBs, detailing second-use applications, re-use, physical recovery, chemical recovery and biorecovery

[From: Recycling lithium-ion batteries from electric vehicles]

Automakers are exploring ways to profit from used batteries:

- ☑ In Japan, Nissan has repurposed batteries to power streetlights. It also leverages used Nissan-Leaf batteries in autonomous robots that deliver parts to its car factories. [[37]].
- ☑ In Michigan, GM is using repurposed batteries from Chevy Volts to back up its data center.
- ☑ In Europe, Volkswagen has already opened a recycling station in Salzgitter, Germany where batteries will be recycled after they can no longer be reused [[38]]. The capacity is 3,600 battery packs per year in the first phase, pilot.

The batteries - at the end of life - will be completely discharged, dismantled, and the components will be ground individually and dried. Through this process, the car company hopes to recover the raw materials needed to produce new batteries, such as copper, aluminum, lithium, manganese, cobalt and graphite. Volkswagen anticipates that it will not receive a large number of batteries in the recycling plant from its electric cars until the end of the decade, so the Salzgitter project will start as a pilot, with the possibility of increasing capacity.

- ☑ In Paris, Renault has batteries backing up elevators.

Renault, the market leader in electric cars in Europe, recycles all used batteries from the models it sells. Groupe Renault has a holistic approach to the battery life cycle: **repairing** first-life batteries to extend their automotive lifespan**,** developing **second-life applications** for energy storage and **setting up a system for collecting and recycling batteries**. In March 2021, Renault joined forces with Veolia and Solvay in order to implement innovative and low-carbon battery recycling solutions to pave the way to sustainable sourcing for strategic battery materials as electric mobility is growing. The consortium wants to recycle batteries from any car manufacturer in the future and reach a market share of 25% in the field [[39]].

Companies do not do this only out of civic responsibility. The material resources used in batteries are limited, and their recovery is essential in the medium and long term.

Raw materials such as cobalt, lithium and nickel are key ingredients for lithium-ion batteries. The mining of these materials can present serious ethical and environmental concerns, including reports of child labor, pollution and heavy water use. What's more, the materials are finite: supply may struggle to meet future demand.

That makes recycling all the more important. Currently, however, the recycling rate for EV batteries is extremely low, with some estimates putting it at five percent. This needs to change for electric mobility to represent a sustainable solution.

The waste-management hierarchy considers re-use to be preferable to recycling. As considerable value is embedded in manufactured LIBs, it has been suggested that their use should be cascaded through a hierarchy of applications to optimize material use and life-cycle impacts. Energy stored over energy invested (ESOI)—the ratio between the energy that must be invested into manufacturing the battery and the electrical energy that it will store over its useful life—is a metric used to compare the efficacy of different energy-storage technologies. Clearly, ESOI figures will improve if end-of-life electric-vehicle batteries can be used in second-use applications for which the battery performance is less critical.

Profitable second-use applications also provide a potential value stream that can offset the eventual cost of recycling, and already a healthy market is developing in used electric-vehicle batteries for energy storage in certain localities, with demand potentially outstripping supply.

The economics of the decision whether to recycle or re-use are set firmly in favor of re-use, mainly because:

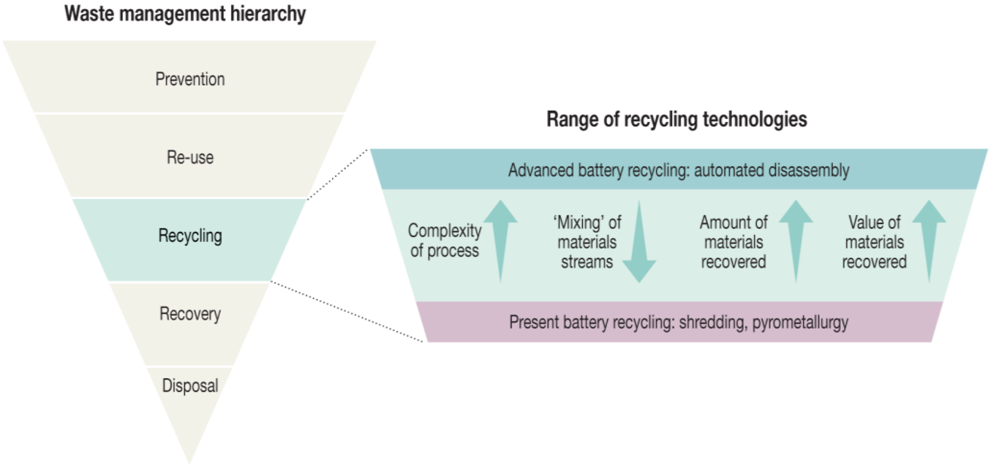
(1) the refurbishment cost of putting the battery into a second-use application;

(2) any credit that would accrue as the result of recycling the battery instead; if the second-use price were to fall below the sum of the refurbishment cost and the recycling credit, then recycling would be the economically favored option.

The stockpiling of waste batteries is potentially unsafe and environmentally undesirable, so, if direct re-use of an LIB module is not possible, it must be repaired or recycled.

End-of-life LIB recycling could provide important economic benefits, avoiding the need for new mineral extraction and providing resilience against vulnerable links and supply risks in the LIB supply chain.

The waste management hierarchy for LIBs is represented in *5-3. Figure*



5-3. Figure_ Waste management hierarchy

[https://doi.org/10.1038/s41586-019-1682-5]

The hierarchy is expanded to consider the range of battery recycling technologies. **PREVENTION** means that LIBs are designed to use less-critical materials (high economic importance, but at risk of short supply) and that electric vehicles should be lighter and have smaller batteries to prevent and reduce waste generation.

RE-USE means that electric-vehicle batteries should have a second use to extend their service lifetime.

RECYCLING means that batteries should be recycled, recovering as much material as possible and preserving any structural value and quality (for example, preventing contamination).

RECOVERY means using some battery materials as energy for processes such as fuel for pyrometallurgy to recover energy from waste.

DISPOSAL means that no value is recovered and the waste goes to landfill.

5.2 DISASSEMBLY OF LIB

5.2.1 CHALLENGES OF PACK AND MODULE DISASSEMBLY

For most remanufacture and recycling processes, battery packs must be disassembled to module level at least.

The hazards associated with battery disassembly are numerous [**Eroare! Marcaj în d ocument nedefinit.**]:

- Disassembly of battery packs from automotive applications requires high-voltage training and insulated tools to prevent electrocution of operators or short-circuiting of the pack.
- Short-circuiting results in rapid discharge, which may lead to heating and thermal runaway.
- Thermal runaway may result in the generation of particularly noxious byproducts, including HF gas, which along with other product gases may become trapped and ultimately result in cells exploding.
- The cells also present a chemical hazard owing to the flammable electrolyte, toxic and carcinogenic electrolyte additives, and the potentially toxic or carcinogenic electrode materials.

BATTERY REPURPOSING—THE RE-USE OF PACKS, MODULES AND CELLS in other applications such as charging stations and stationary energy storage—requires an accurate assessment of both the state of health, to categorize whether batteries are best suited for re-use (and if so, for which applications), remanufacture or recycling, and the state of charge, for safety reasons in some recycling processes.

For high-throughput triage and gateway testing of batteries at scale, the optimal approach involves in situ techniques for monitoring cells in service to enable advance warning of possible cell replacement, and module or pack reconditioning, rather than complete repurposing at a low level of state of health owing to a few failing cells.

Is expected that more advanced diagnostic functionality will be embedded in battery management systems, providing data that can be interrogated at end-of-life.

A challenge for battery recycling stems from the fact that vehicle manufacturers have taken different approaches to powering their vehicles, and EVs on the market have a wide variety of physical configurations, cell types, and cell chemistries.

The differing form factors and capacities may also restrict applications for re-use.

For reuse and recycling applications, car batteries are currently disassembled manually. The weights and high voltages of the batteries mean that such disassembly requires skilled personnel and specialized tools.

There is concern that untrained mechanics may risk their lives repairing electric vehicles [40], or handling vehicles at the end-of-life.

Vehicle design must reach compromises between crash safety, center of gravity and space optimization, which must be balanced with functionality. These conflicting design goals often lead to designs that are not optimized for recyclability and can be time- and money-consuming for manual disassembly [36].

5.2.2 AUTOMATING BATTERY DISASSEMBLY

Robotic battery disassembly could eliminate the risk of harm to human workers, and increased automation would reduce cost, potentially making recycling economically viable.

Automation could also improve the mechanical separation of materials and components, enhancing the purity of segregated materials and making downstream separation and recycling processes more efficient.

The automation of the dismantling of automotive batteries presents major challenges because robotics and automation in the manufacturing sector rely on highly structured environments, in which robots make pre-programmed repetitive actions with respect to exactly known objects in fixed positions.

In contrast, the development of robotic systems that can generalize to a variety of objects, and handle uncertainty, remains a major challenge at the frontier of artificial intelligence research. It is important to consider the complexity of vehicle battery disassembly from this perspective.

At present there is no standardization of design for battery packs, modules or cells within the automotive sector, and it is unlikely that this will happen in the near future. Also, much of the factory assembly of these batteries is done by human workers and remains unautomated. Their disassembly and waste-handling typically involve even less structured environments, with much greater uncertainties, than a manufacturing assembly line.

The Society for Automotive Engineers and the Battery Association of Japan have both recommended labeling standards for electric-vehicle batteries. Recent algorithms from computer vision research have some capability to recognize objects and materials on the basis of features such as size, shape, colour and texture.

It could be advantageous for recycling if manufacturers were to (some manufacturers already do) include labels, QR Codes, RfID tags or other machine-readable features on key battery components and sub-structures. Where these provide a reference to an external data source, its utility in aiding the recycling process will depend on the accessibility and format of that data. If proprietary and private, such data are of limited use, but there may be initiatives to move towards standardization and open data formats [36].

A number of companies are considering blockchain technologies to provide whole-life-cycle tracking of battery materials, including information and transparency on provenance, ethical supply chains, battery health and previous use. China has signalled its intention to track battery materials.

Due to the complexity of automotive battery packs, the possibility of human-robot collaboration using a new generation of force-sensitive "co-bot" robot arms has been suggested [[41]].

Unlike conventional industrial robots, these co-bots can safely share a workspace with humans, and the robot could be taught tasks like unscrewing screws while the human handles more cognitively complex tasks. However, this approach does not protect the human worker from battery hazards.

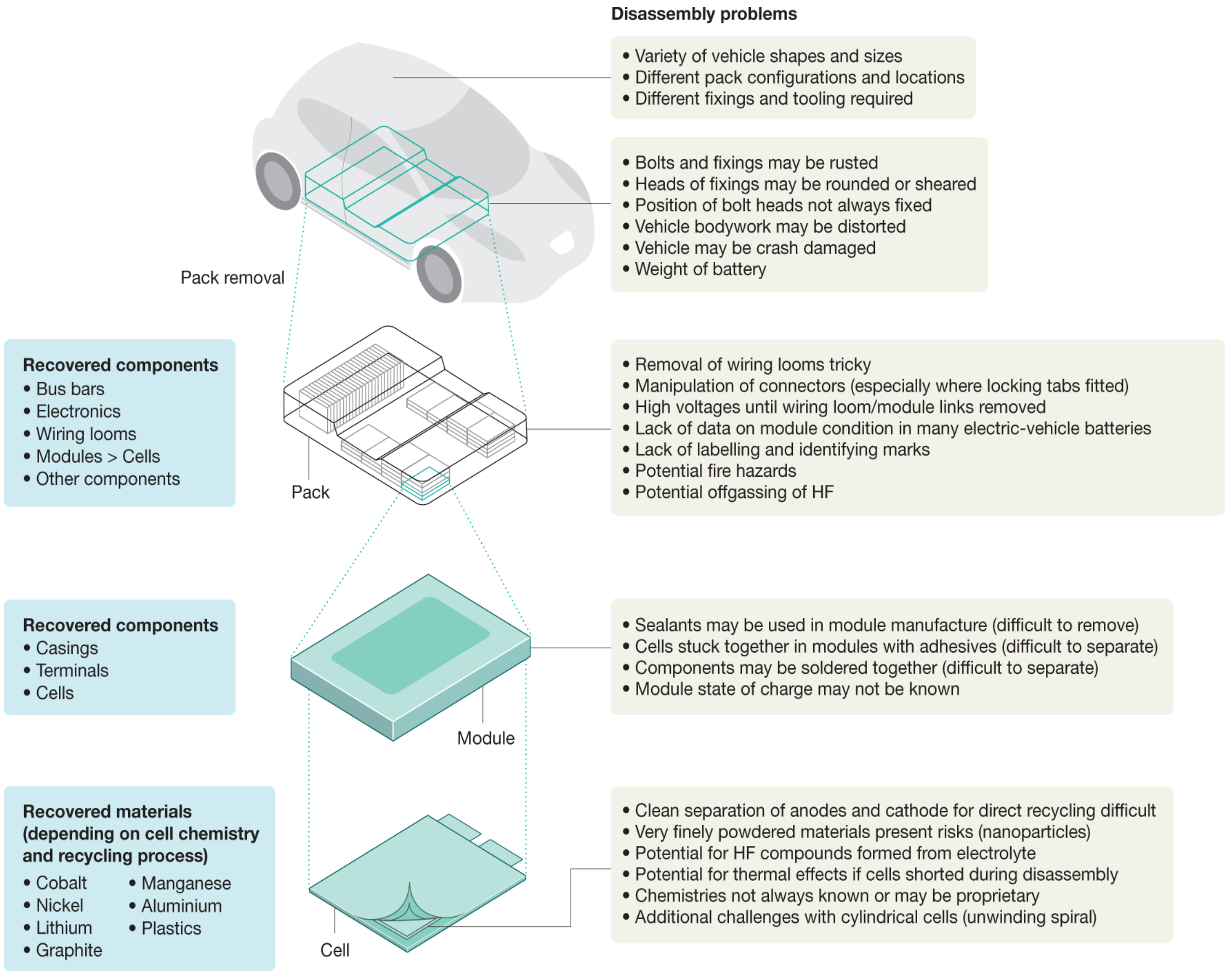
Using current industrial robotics methods, the problem only becomes attemptable (but still difficult) provided that the position of the bolt head is always exactly fixed, in a known pose relative to the robot, with very high precision.

State-of-the-art robotics, computer vision and artificial-intelligence capabilities for handling diverse waste materials do exist, and these systems have demonstrated sufficient robustness and reliability to gain acceptance by the UK nuclear industry, for example, in the deployment of artificial-intelligence-controlled, machine-vision-guided robotic manipulation for cutting of contaminated waste material in radioactive environments [[42]].

These technologies are now being adapted to the demanding problem of robotic battery disassembly.

At different scales of disassembly—pack removal, pack disassembly, module removal and cell separation—different challenges and barriers to automation exist.

Some of these are set out in *5-4. Figure*



5-4. Figure_Challenges of disassembly at different levels of scale

[https://www.nature.com/articles/s41586-019-1682-5#Fig1]

Electric-vehicle battery packs are complex in design, containing wiring looms, bus bars, electronics, modules, cells and other components. There are also many different types of fixtures and fastenings, including screws, bolts, adhesives, sealants and solders, which are not designed for robotic removal.

Computer-vision algorithms are being developed that can identify diverse waste materials and objects [43], reliably track objects in complex, cluttered scenes [44], and dynamically guide the actions of robot arms [45].

DISMANTLING requires forceful interaction between robots and objects, engendering complex dynamics and control problems, such as simultaneous force and motion control, which is needed for robotic cutting or unscrewing.

Dismantled materials must be grasped and manipulated, including fragmented or deformable materials, which pose challenges both to vision systems and autonomous grasp planners.

Demonstrated state-of-the-art performance in autonomous, vision-guided robotic grasping of arbitrary objects from random, cluttered heaps. These advances in computer vision, artificial intelligence and robotics fundamentals offer exceptionally promising tools with which to approach the extremely difficult open research challenge of automated disassembly of electric-vehicle batteries [46].

Table 5.1 Typical intelligent methods for disassembly operations of electric-vehicle batteries [46]

Tasks	**Methods**	**Advantages**	**Disadvantages**
Computer vision based disassembly target detection	Region-proposal based two-stage detection	Bottom-to-up selective search Separate steps for region proposal and region classification High detection accuracy Capable of handling multi-scale and small object detection	Slow learning speed compared to single stage models Complex architectures
	Region free one-stage detection	Global regression Simple pipeline High learning speed for real-time detection	Low localization precision for small objects compared to region proposal-based models
Cutting process optimization	Multi-objective metaheuristic optimization	Global search in the process combinatorial parameter space	Local optima Slow convergence for large scale optimization
	Clustering/ classification	Capable of identifying the relationships between the process inputs and outputs	Lack of sufficient experimental data
	Neural network	Prediction ability of the process effect	Require sufficient training Lack of sufficient experimental data
Robotic grasping /handling	Sim2real learning with domain randomization for universal picking	No need for tedious empirical data collections	High computation burden in synthetic dataset generation Dependent on the training dataset Simulation-to-reality gap
	Self-supervised learning	Automatically collect unlabeled realworld data for learning No need for expensive manual labeling	Require expertise on pretext task design
	Learning from imitation/ demonstration	No need to manually specify imprecise models No need for prior reward function design	Require high quality and sufficient demonstrations Limited generalization capability
	Combined self-supervised and imitation learning for deformable objective	Combining the learned goal-directed inverse dynamics model with highlevel human direction	Limited generalization capability for new objects and complex tasks

	manipulation		

Table 5.2 Intelligent solutions to addressing EV-LIB disassembly challenges [46]

Challenges	**Intelligent requirements Intelli**	**Intelligent requirements Intelligent solutions**
Safety risks	Autonomous disassembly process	Autonomous checking, testing, and sorting Intelligent target detection Robotic separation and manipulation
	Remote control and operation	Teleoperation by direct/indirect/shared control
	Active collision avoidance	Intelligent recognition and prediction of human activities, intelligent motion planning
	Environment monitoring and control	Multimodal CPS based risk prevention
	Green and hazard-free LIB design	Intelligent eco-design of new battery materials
Design variety	Model recognition and identification	Intelligent recognition
	High-flexibility and adaptive disassembly capability	Adaptive and flexible disassembly planning Intelligent target detection Generic and dexterous robotic manipulation
	New design of standard EV-LIBs	Intelligent eco-design methods
Uncertain conditions	Uncertainty perception and estimation	Intelligent recognition and EV-LIB state prognostics Intelligent target detection and abnormal detection Disassembly effects prediction
	Human-robot interaction	Shared control with robot's learning capability Human perception + multimodal sensors
	Uncertainty response capability	Intelligent process optimization Flexible manipulation capability Context-aware and dynamic planning/scheduling
Difficult for robotic disassembly	Separation process optimization	Versatile and efficient disassembly functions/tools
	Dexterous manipulation	Robotic manipulation of deformable components
	Human-robot interaction and collaboration	Incorporate human's manipulation flexibility and dexterity
	Design for easy disassembly	Intelligent eco-design for active or easy disassembly
Lack of data	Intelligent identification and sharing	Intelligent labeling with IoT system
	High-throughput testing	Robotic testing
	All-stakeholder cooperation	Cloud disassembly
	Human-robot collaboration	Incorporate human's manipulation perception and flexibility

Once LIBs have been designated for recycling, the three main processes involved consist of stabilization, opening and separation, which may be carried out separately or together.

LIB CELLS CAN BE SHREDDED AT VARIOUS STATES OF CHARGE, and from a commercial point of view, if discharged modules or cells are to be processed in this way, discharge prior to shredding adds cost to the processes. Furthermore, exactly what the optimum level of discharge might be remains unclear. Depending on cell chemistry and depth of discharge, over-discharging of cells can result in copper dissolution into the electrolyte. The presence of this copper is detrimental for materials reclamation as it may then contaminate all the different materials streams, including the cathode and separator. If the voltage is then increased again or 'normal' operation resumed55, this can be dangerous because copper can reprecipitate throughout the cell, increasing the risks of short-circuiting and thermal runaway.

Current LIB-processing technologies essentially bypass these concerns by feeding end-of-life batteries directly into a shredder or high-temperature reactor.

Industrial comminution technologies can passivate batteries directly but recovered battery materials then require a complex set of physical and chemical processes to produce usable materials streams.

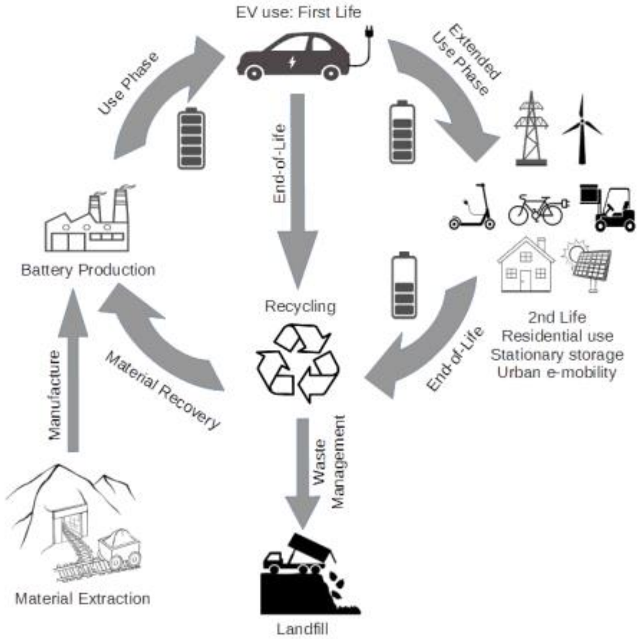
PYROMETALLURGICAL RECYCLING PROCESSES at scale may be able to accept entire electric-vehicle modules without further disassembly.

However, this solution fails to capture much of the embodied energy that goes into LIB manufacture, and leaves chemical separation techniques with much to do as the battery materials become ever more intimately mixed.

5.3 REUSE OF ELECTRIC VEHICLE BATTERIES

The Circular Energy Storage report [[47]] shows that the average age of light duty EV batteries will be 14.7 years when they reach the first end of life, with 50% having reached end of life after 15 years. Also, the battery age is not only connected to battery performance but as much to the actual application, ownership, value and user behavior.

After the old battery is removed from the vehicle, it is evaluated and usually enters a second life. Despite having a smaller storage capacity, the battery can still serve a useful purpose. Old batteries can be used in applications that are not as demanding as powering a vehicle. For example, a battery can be used for stationary energy storage to support the local utility company's electricity grid. Redirecting the battery to a second circuit of use, where the useful life is extended, offers alternative energy storage services, thus reducing the environmental impact per kWh provided by the battery. A representation of battery life from a circular economy perspective is shown in *5-5. Figure* [[48]].



5-5. Figure_ Battery life cycle in a circular economy perspective

[Source: Kotak, Y et all, End of Electric Vehicle Batteries: Reuse vs. Recycle]

The transition from a linear to a circular value chain can improve both the environmental and the economic footprint of batteries, by obtaining more results from used batteries and by capitalizing on the end of life.

EXAMPLES OF EV BATTERIES SECOND LIFE

Not all used batteries are redundant once they are removed from an EV. Although they may no longer be able to power a vehicle, many still have sufficient capacity for other functions. Nissan and Volkswagen, for example, are now reusing old EV batteries in some of their factory robots.

Other batteries are being repurposed by "upcycling businesses" like Batteries that USES SECOND-HAND EV BATTERIES TO POWER FISHING BOATS OR AS MOBILE POWER UNITS FOR REMOTE LOCATIONS. Solving this problem will require vehicle manufacturers, battery makers and third parties to work hand in hand.

SUSTAINABLE ENERGY BUSINESS IN YELLOWSTONE NATIONAL PARK

In June 2014, the partnership among Toyota, Indy Power Systems, Sharp USA SolarWorld, Patriot Solar, National Park Service, and Yellowstone Park Foundation, end-of-life Toyota Camry Hybrid nickel-metal hydride battery packs that store energy generated by solar panels in the distributed energy system started operation in Yellowstone National Park. Renewable electricity that was generated by solar panels is stored in the 208 used Camry Hybrid NiMH battery packs (with a capacity of 85kWh), and is used as an emergency power supply for lodges in the park [[49]].

5.4 LITHIUM ION BATTERY RECYCLING

Manufacturers typically guarantee an EV lithium-ion battery for seven to eight years, or 100,000 miles of use, although they often last longer. Rather than reusability, they have traditionally been built for performance and durability.

Lithium-ion batteries have been recycled for more than 15 years, but with different efficiencies and recovery rates. Recycling must be managed properly, as toxic chemicals inside old batteries can lead to water and soil contamination. As part of the recycling process, they are melted to recover lithium, cobalt and nickel. However, this can be costly, so reusing used batteries can be more cost effective. Many EVBs still have up to 70% of their capacity [[50]], which means they can be used for many other energy storage needs.

Lithium-ion batteries, which use hazardous metals, stain the green image of electric vehicles. Recycling to recover those precious metals would minimize the social and environmental impact of mining, save millions of tonnes of batteries from landfills and reduce energy consumption and emissions from battery manufacturing.

But as the EV battery recycling industry begins to grow, convincing carmakers to use recycled materials remains a difficult task, as people's impression is that recycled material is not as good as virgin material and battery companies are still hesitant to use recycled material in their batteries [[51]].

EV batteries are large and heavy, comprising several hundred individual cells, all of which need dismantling. However, most components are welded together, which is good for electrical connection, but bad for efficient recycling. It can also be dangerous work: cut into the wrong place and a battery can short-circuit, combust and release toxic fumes.

But things are changing. The latest EVs now have solid-state batteries, which are smaller, less complex and not as flammable. An example is the new Blade Battery, launched in March 2020 from Chinese firm BYD, that is higher in terms of performance, safety and recyclability – thanks to its modular design. Another unique point of the blade battery is that it uses lithium iron-phosphate (LFP) as the cathode material, which offers a much higher level of safety than conventional lithium-ion batteries. LFP naturally has excellent thermal stability and is substantially cobalt free. LFP is also a very durable material [[52]].

Spent LIBs contain not only highly valuable and scarce Li, Co, and Ni metals; but also Fe, Cu, Al, P, and other elements with low concentrations. From the economic point of view, the recovery of S-LIBs mainly focuses on recycling highly valuable Co, Li, and Ni metals from CAMs; the recovery of graphite-containing anode materials and the electrolyte is hardly stated [[53]].

Traditionally, lithium-ion battery recycling relies on two techniques, used separately or in combination: **PYROMETALLURGY AND HYDROMETALLURGY**. For the former, which is more common, recyclers shred and then burn the batteries, before extracting the metals. In hydrometallurgy, batteries are dissolved in acid, leaving a metal “soup” ready for extraction.

Neither is ideal: pyrometallurgy is energy-intensive, while the alternative uses potentially harmful chemicals.

PYROMETALLURGY destroys the organic and plastic components by exposing them to high temperatures and leaves only the metal components (nickel, cobalt, copper, etc.). These components are then separated by chemical processes.

HYDROMETALLURGY does not include the high-temperature stage. Instead, it separates the components only by different baths of solutions that are chemically adapted to the materials to be recovered.

In both cases, the batteries must first be ground to a powder.

The two processes currently operate on an industrial scale in recycling LIBs for telephones and laptops to recover the cobalt they contain. This material is so precious that recovering it ensures the economic profitability of the current LIB recycling sector.

But as the LIB technologies used for EVs do not all contain cobalt, the question of the economic model for recycling them remains unresolved, and there is still no real industrial sector for recycling these batteries. The main reason is the lack of a sufficient volume of batteries to be processed: the widespread roll-out of EVs is relatively recent and their batteries are not yet at the end of their life.

Furthermore, the definition of this end of life is in itself subject to discussion. For example, “traction” batteries (which allow EVs to run) are considered unfit for service when they have lost 20 or 30% of their capacity – which corresponds to an equivalent loss in the vehicle’s autonomy.

The EV battery recycling market is currently a small one, comprising around 100 companies worldwide, but it is growing.

Sweden’s Northvolt Company combine battery recycling with manufacturing. Founded by Tesla’s former supply chain head, it was recently valued at almost $12 billion and has racked up orders worth a reported $27 billion. The company is currently building a huge 500,000-square-metre factory in Sweden as part of its plan to create a “circular European battery industry” [[54]].

In the United States, another Tesla alumnus, co-founder and former CTO JB Straubel, has set up **REDWOOD MATERIALS** a company that [[55]]:

- ☑ takes e-waste from a variety of industries before sending repurposed materials to battery makers like Panasonic and has already reached a multi-billion-dollar valuation;
- ☑ transforms the battery supply chain by offering large-scale sources of domestic anode and cathode materials produced from an increasing number of recycled batteries that directly go back to U.S. cell manufacturers;
- ☑ creates a closed-loop, domestic supply chain for lithium-ion batteries across collection, refurbishment, recycling, refining, and remanufacturing of sustainable battery materials.

Recycling for LIB usually involves both physical and chemical processes [[56]]. Due to the complex process of assembling the LIBs and the wide variety of electrodes, the process of battery recovery involves a high risk of accidents due to explosion, combustion and the resulting harmful gases. [[57]]. To reduce this risk, used LIBs should usually be discharged before recycling.

PHYSICAL PROCESSES usually include pretreatment and direct recovery of electrode materials [[58]]. These processes usually include disassembly, crushing, screening, magnetic separation, washing, heat treatment, etc.

CHEMICAL PROCESSES can be divided into pyrometallurgical and hydrometallurgical processes, which usually involve leaching, separation, extraction and chemical/ electrochemical precipitation.

Currently, the hydrometallurgical process is commonly used to recover LIBs after pretreatment.

The pyrometallurgical process is widely used for the commercial recovery of Co.

The direct physical recycling process is a process of recovering useful components from used LIBs without using chemical methods.

5.4.1 PYROMETALLURGICAL RECOVERY

Pyrometallurgical metals reclamation uses a high-temperature furnace to reduce the component metal oxides to an alloy of Co, Cu, Fe and Ni. The high temperatures involved mean that the batteries are ‘smelted’, and the process, which is a natural progression from those used for other types of batteries, is already established commercially for consumer LIBs. It is particularly advantageous for the recycling of general consumer LIBs, which currently tends to be geared towards an imperfectly sorted feedstock of cells (indeed, the batteries can be processed along with other types of waste to improve the thermodynamics and products obtained), and this versatility is also valuable with respect to electric-vehicle LIBs.

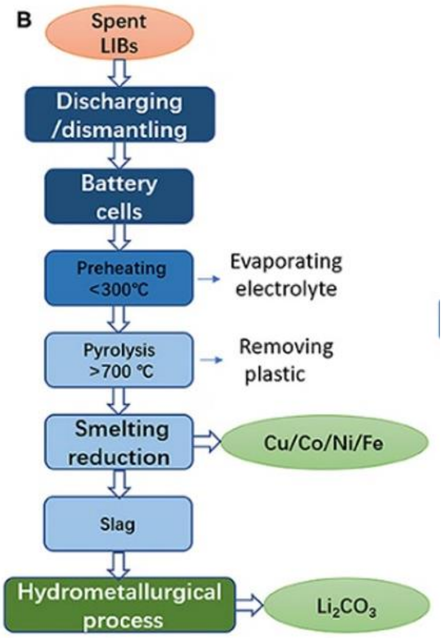
As the metal current collectors aid the smelting process, the technique has the important advantage that it can be used with whole cells or modules, without the need for a prior passivation step.

The products of the pyrometallurgical process are a metallic alloy fraction, slag and gases. The gaseous products produced at lower temperatures (<150 °C) comprise volatile organics from the electrolyte and binder components. At higher temperatures the polymers decompose and burn off. The metal alloy can be separated through hydrometallurgical processes (see section 'Hydrometallurgical metals reclamation') into the component metals, and the slag typically contains the metals aluminium, manganese and lithium, which can be reclaimed by further hydrometallurgical processing, but can alternatively be used in other industries such as the cement industry.

There is relatively little safety risk in this process, as the cells and modules are all taken to extreme temperatures with a reductant for metal reclamation—aluminium from the electrode foils and packaging is a major contributor here—so the hazards are contained within the processing. In addition, the burning of the electrolytes and plastics is exothermic and reduce the energy consumption required for the process.

It follows that in the pyrometallurgical process there is typically no consideration given to the reclamation of the electrolytes and the plastics (approximately 40–50 per cent of the battery weight) or other components such as the lithium salts.

Despite environmental drawbacks (such as the production of toxic gases, which must be captured or remediated and the requirement for hydrometallurgical post-processing), high energy costs, and the limited number of materials reclaimed, this remains a frequently used process for the extraction of high-value transition metals such as cobalt and nickel [59].



5-6. Figure_((B) Pyrometallurgical process

[source: Zhou Li-Feng, et all „The Current Process for the Recycling of Spent Lithium Ion Batteries”]

The pyrometallurgical process is widely used for the commercial recovery of Co.

5.4.2 PHYSICAL MATERIALS SEPARATION

For reclamation after comminution, recovered materials can be subjected to a range of physical separation processes that exploit variations in properties such as particle size, density, ferromagnetism and hydrophobicity.

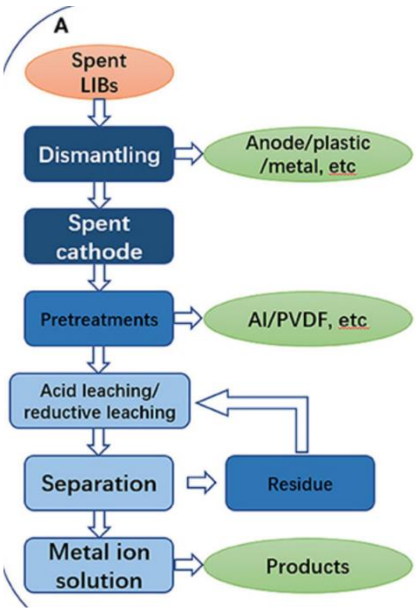
These processes include sieves, filters, magnets, shaker tables and heavy media, used to separate a mixture of lithium-rich solution, low-density plastics and papers, magnetic casings, coated electrodes and electrode powders.

The result is generally a concentration of electrode coatings in the fine fractions of material, and a concentration of plastics, casing materials, and metal foils in the coarse fractions [36]. The coarse fractions can be put through magnetic separation processes to remove magnetic material such as steel casings and density separation processes to separate plastics from foils.

The fine product is referred to as the 'black mass', and comprises the electrode coatings (metal oxides and carbon). The carbon can be separated from metal oxides by froth flotation, which exploits the hydrophobicity of carbon to separate it from the more hydrophilic metal oxides [[60]].

5.4.3 HYDROMETALLURGICAL METALS RECLAMATION

Hydrometallurgical treatments involve the use of aqueous solutions to leach the desired metals from cathode material. By far the most common combination of reagents reported is H_2SO_4/H_2O_2 [36].



5-7. Figure_ (A) Hydrometallurgical process

[source: Zhou Li-Feng, et all „The Current Process for the Recycling of Spent Lithium Ion Batteries”]

A number of studies have been carried out in order to determine the most efficient set of conditions to achieve an optimal leaching rate. These include: concentration of leaching acid, time, temperature of solution, the solid-to-liquid ratio and the addition of a reducing agent [[61]].

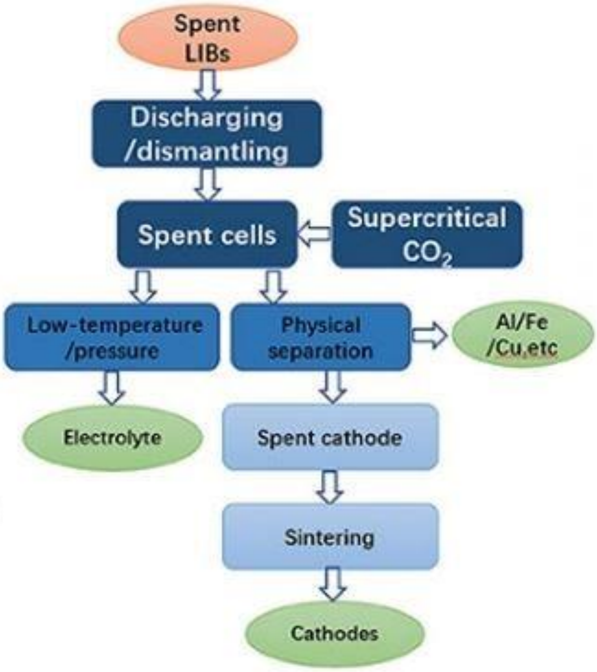
Currently, the hydrometallurgical process is commonly used to recover LIBs after pretreatment.

5.4.4 DIRECT RECYCLING

The removal of cathode or anode material from the electrode for reconditioning and re-use in a remanufactured LIB is known as direct recycling. In principle, mixed metal-oxide cathode materials can be reincorporated into a new cathode electrode with minimal changes to the crystal morphology of the active material.

In general, this will require the lithium content to be replenished to compensate for losses due to degradation of the material during battery use and because materials may not be recovered from batteries in the fully discharged state with the cathodes fully lithiated. So far, work in this area has focused primarily on laptop and mobile phone batteries, as a result of the larger amounts of these available for recycling [36].

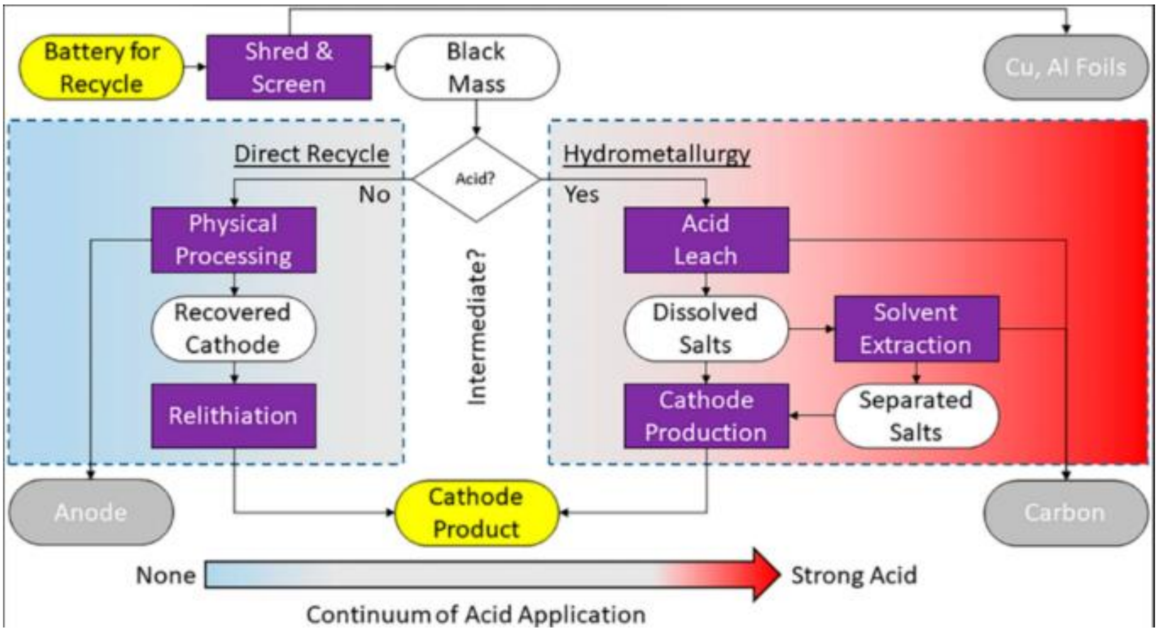
The direct physical recycling process (*5-8. Figure*) is a process of recovering useful components from used LIBs without using chemical methods.



5-8. Figure_(C) Direct physical recycling process

[source: Zhou Li-Feng, et all „The Current Process for the Recycling of Spent Lithium Ion Batteries”]

A hydrometallurgical process - which uses an acidic solution to separate complex chemicals into individual elements - is more expensive, consumes more energy and is more complex, but has the advantage of being interoperable between different systems in terms of cathode chemistry [62]. However, it recovers only about half of the battery mass. *5-9. Figure* shows the direct recycling and recycling by hydrometallurgical process.



5-9. Figure_ Direct recycling vs. hydrometallurgy
[source:https://www.engineering.com/story/closing-the-loop-on-li-ion-battery-recycling]

Direct recycling also has the advantage that, in principle, all battery components can be recovered and reused after further processing (with the exception of separators).

The efficiency of direct recycling processes is correlated with the health of the battery and may not be advantageous where the state of charge is low. There are also potential problems with the flexibility of these routes to handle metal oxides of different compositions.

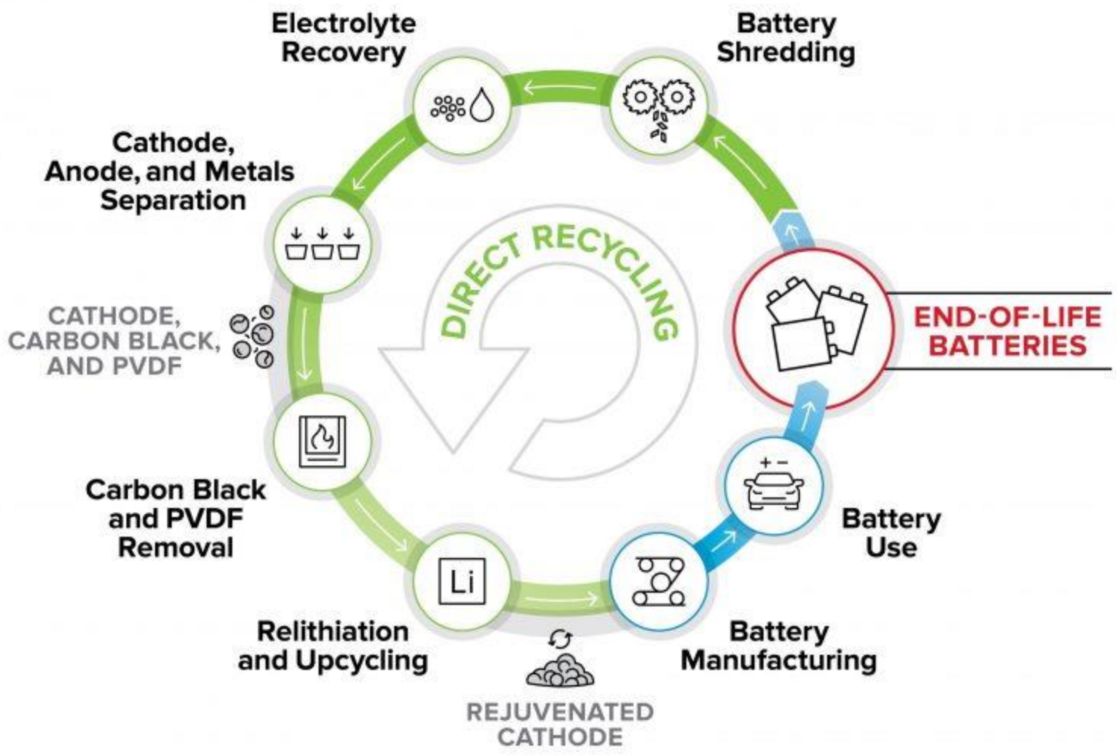
Direct recycling may have difficulty accommodating raw materials of unknown or poorly characterized provenance, and there will be commercial reluctance to reuse the material if product quality is affected.

5.4.5 RECELL CENTER

The U.S. Department of Energy established the ReCell Center in 2019 to develop robust LIB recycling technology that would be economical even for batteries that contain no cobalt. The central feature of the technology is recovery of the cathode material with its unique crystalline cathode morphology intact in order to retain its value and functionality [63].

This allows a reduction in the GHG intensity of the value chain by 34 megatons (Mt), while creating an additional economic value of about $ 35 billion. Grid Vehicle (V2G) solutions could reduce costs for electric vehicle charging infrastructure by up to 90%, and in 2030 could cover 65% of demand for global battery storage networks[[64]].

The concept of **direct recycling**, patented in the United States for the first time in 2009 [[65]], is simple: the crystalline structure of the cathode must be kept intact.

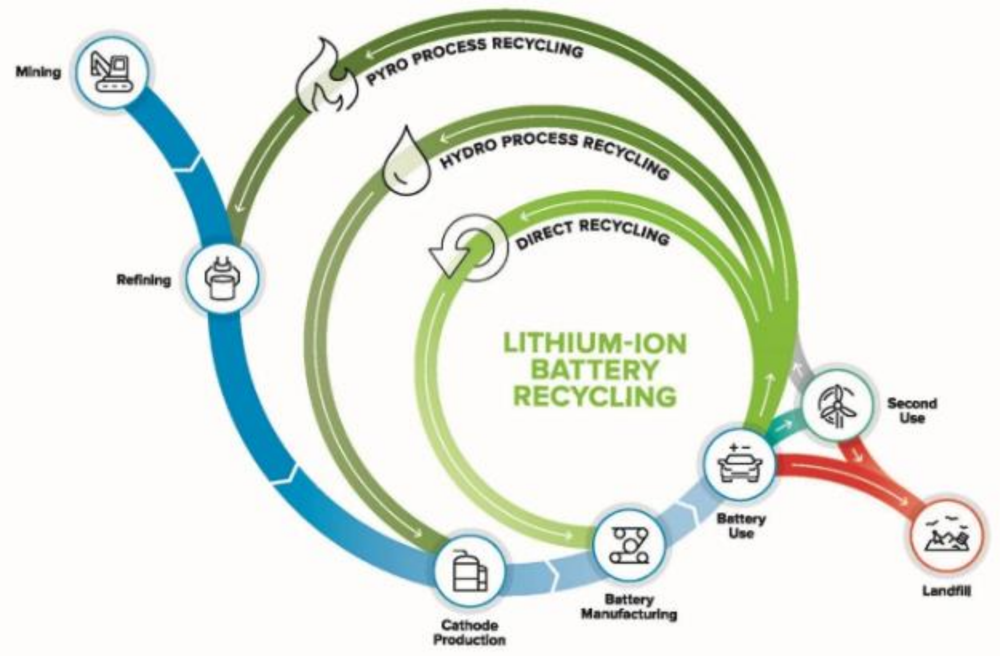


5-10. Figure_ Direct Recycling - A schematic showing processes that a direct recycling process may include

[Argonne National Laboratory https://recellcenter.org/research/direct-recycling-of-materials/]

ReCell R&D defines direct recycling as the recovery, regeneration and reuse of battery components directly, without destroying the chemical structure. It has also been called direct cathode recycling and cathode-to-cathode recycling.

By recovering the cathodic material, several energy-consuming and expensive processing steps can be avoided. The scope of ReCell R&D also includes the recovery of as many materials as possible, in accordance with the principles of the circular economy. Not only does the recovery of multiple materials offer potential additional revenue, but the costs and other impacts of waste treatment can be avoided.



5-11. Figure_ Lithium-ion battery lifecycle

[source: Gaines, L.; Dai, Q.; Vaughey, J.T.; Gillard, S. "Direct Recycling R&D at the ReCell Center". Recycling 2021]

ReCell is working to drive the development of new technologies for direct recycling and focuses on generating as much value as possible from the components inside of a battery. It is important to design all down-stream processing and material recovery sequences in a way that preserves integrity, assures high salvage rate, and yields high purity materials [66].

The research in this focus area centers around the following themes:

- ☑ **Electrolyte Recovery**: Investigate methods that allow the valuable lithium salts and organic electrolyte solvents to be recovered from spent batteries.
- ☑ **Electrode Separation and Recovery**: Separate mixtures of electrode materials using techniques based on their unique properties, such as hydrophobicity, density, and magnetic susceptibility.
- ☑ **Binder Removal**: Determine the most effective method to remove the binder holding electrode particles together with minimal damage to the particles' performance so that costly after-treatment processes are not required.
- ☑ **Cathode Relithiation**: Develop an energy-efficient process to directly regenerate cycled, degraded cathode active particles (LCO, LMO, NCM, NCA, and their mixtures) to revive their high electrochemical performance.
- ☑ **Graphite Recovery**: Recover and upcycle spent graphite anode material through surface purification, such that beneficial SEI components are retained while performance-inhibiting species are selectively removed.

- ☑ **Cathode Upcycling and Impurity Impact**: Upgrade obsolete cathode chemistries to those the battery industry is currently using. Understand how impurities generated during processing (e.g., Cu, Al, Fe, etc.) impact material performance.

5.4.6 LI-CYCLE METHOD

Spoke & Hub technologies from Li-Cycle [67] use a combination of safe mechanical size reduction and recovery of hydrometallurgical resources designed specifically for recycling lithium-ion batteries.

Li-Cycle stated that its method can recover 95% of a battery's materials using an environmentally friendly, safe, scalable and economically viable process. Li-Cycle handles hazardous materials in strategically placed spaces with modular, scalable facilities that unload, disassemble, crush and sort - before transporting safe components to a central chemical separation hopper. The process recovers graphite, cobalt, nickel, copper, manganese and lithium from current Li-ion batteries.

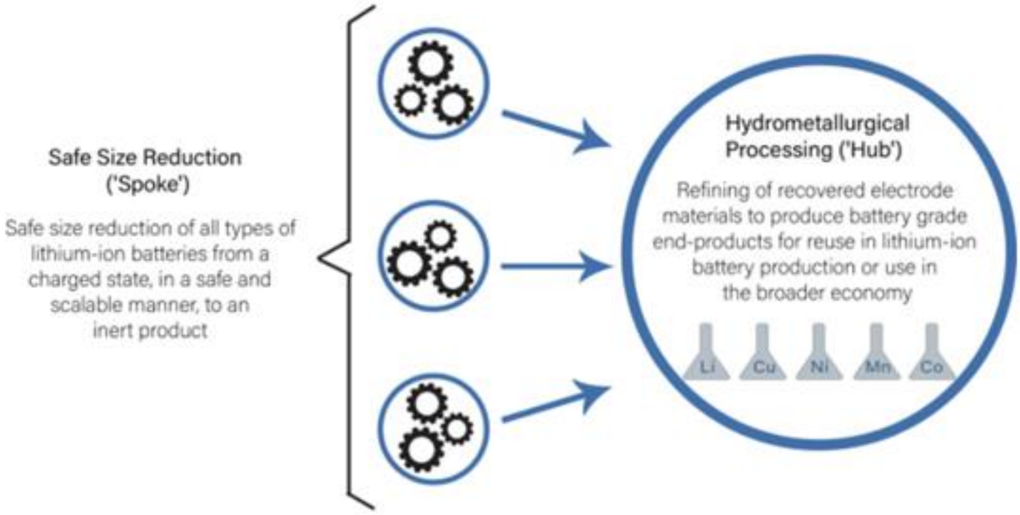


Figure 5-12: „Spoke and Hub" Method from Li-Cycle

[source: https://li-cycle.com/technology/]

Li-Cycle started in 2016, conducting two years of research and development before building a demonstration hub.

5.4.7 DUESENFELD RECYCLING METHOD FOR MATERIAL RECOVERY

German firm Duesenfeld is a dedicated lithium-ion battery recycler. It uses a patented method that combines mechanical, thermodynamic and hydrometallurgical processes to extract high-quality recycled materials from batteries. This is important: some recycled battery metals are only suitable for use as "inferior" materials in areas like construction, but Duesenfeld says it can deliver battery-ready secondary raw materials.

Duesenfeld [68] claims that his recycling process can recover over 90% of a battery's material, using an environmentally friendly method that avoids the energy-intensive smelting process used in most battery recycling operations.

For safety, Duesenfeld uses a decentralized system that minimizes travel distance to its recycling facilities. Upon arrival at a collection unit, the batteries are discharged and disassembled slowly. The cells are then crushed in an inert nitrogen atmosphere to prevent spontaneous ignition. The electrolytes are evaporated and recovered in vacuo, while the crushed material, which is now safe to transport, is sent to a central plant for further processing.

After mechanical sorting, the company's patented hydrometallurgical method separates the remaining material to recover cobalt, lithium, nickel, manganese and graphite.

Duesenfeld company evolves an integrated procedure of mechanical process, thermodynamic process, and hydrometallurgy to recycle spent LIBs. This battery recycling approach is adopted from the LithoRec pathway [69].

5.4.8 LITHOREC – RECYCLING OF LITHIUM ION BATTERIES

One possible recycling process of LIB is that proposed by the German project consortium “LithoRec II – Recycling of Lithium Ion Batteries II”. The LithoRec and LithoRec 2 consortiums aim at developing and assessing powerful processes and full life-cycle concepts for industrial recycling of used Li-Ion batteries in Germany in an ecological and economical efficient manner [70].

The recycling procedure aims at recovering high-purity cathodic substances from spent EV batteries, the facility offers an annual operating capacity of 2000 tons/year.

The lithoRec process starts with a deep battery discharge process to obviate explosions and reduce the danger associated with the high voltages (up to 400 V).

Following that, the discharged batteries are disassembled manually to eliminate peripherals like protective cases, plastics, wiring, and contaminants.

The disassembled batteries are subsequently shredded by a crusher (20 mm) under an N2 atmosphere between 100–140 ◦C.

The shredded material is transported into a zig-zag air classifier, where plastic, copper, iron, and aluminum are segregated. The fine fraction (black mass) containing mainly cathode and anode substances undergoes a secondary crushing step and a sieving process (500 µm of sieving size).

After sieving, the particle size fraction above 500 µm is sent to a second air classifier, where it is divided into proportions consisting of plastics, copper, and aluminum. The other fraction below 500 µm is transferred to hydrometallurgical processing where the material is dissolved in an unrevealed leachant.

Graphite is eliminated firstly from the solution in the dissolution step, this is ensued by manganese, cobalt, and nickel, these elements are precipitated in the form of metal oxides. Lithium leached out in the leachate is recovered in a medley of Li2CO3 and LiOH through a precipitating process.

Raw materials are obtained after further treatment of both fractions.

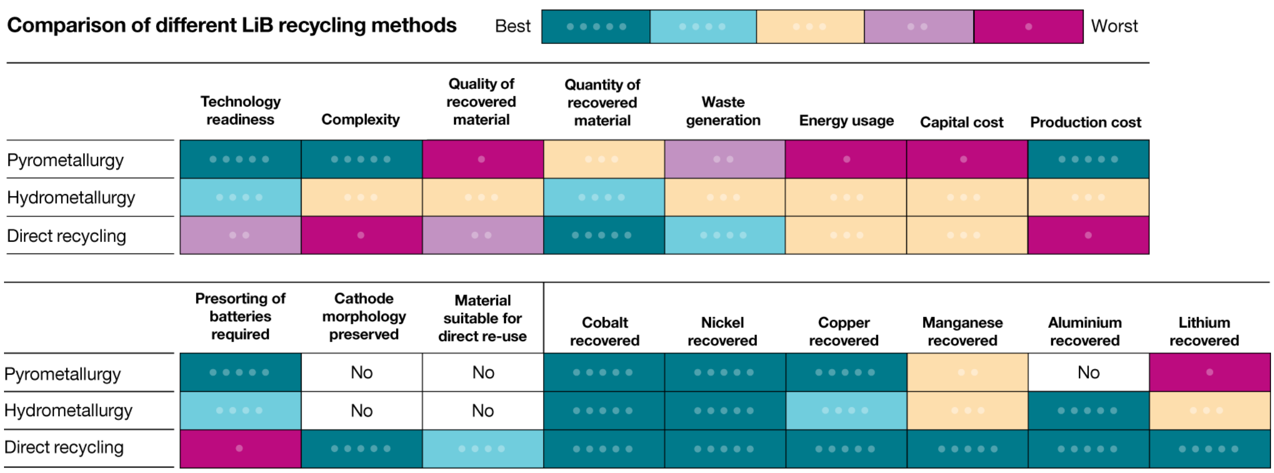
The objective of the LithoRec project, by realizing this process, is to gain high-quality secondary raw materials that can be used in the production of new batteries or other industrial products, hence closing the materials cycle for lithium ion batteries.

5.4.9 BIOLOGICAL METALS RECLAMATION

Bioleaching, in which bacteria are harnessed to recover valuable metals, has been used successfully in the mining industry. This is an emerging technology for LIB recycling and metal reclamation and is potentially complementary to the hydrometallurgical and pyrometallurgical processes currently used for metal extraction; cobalt and nickel, in particular, are difficult to separate and require additional solvent-extraction steps. The process uses microorganisms to digest metal oxides from the cathode selectively and to reduce these oxides to produce metal nanoparticles. The number of studies that have been performed thus far, however, is relatively small and there is plenty of opportunity for further investigation in this field [36].

5.5 COMPARISON OF LIB RECYCLING METHODS

The recycling methods discussed are compared in *5-13. Figure*.



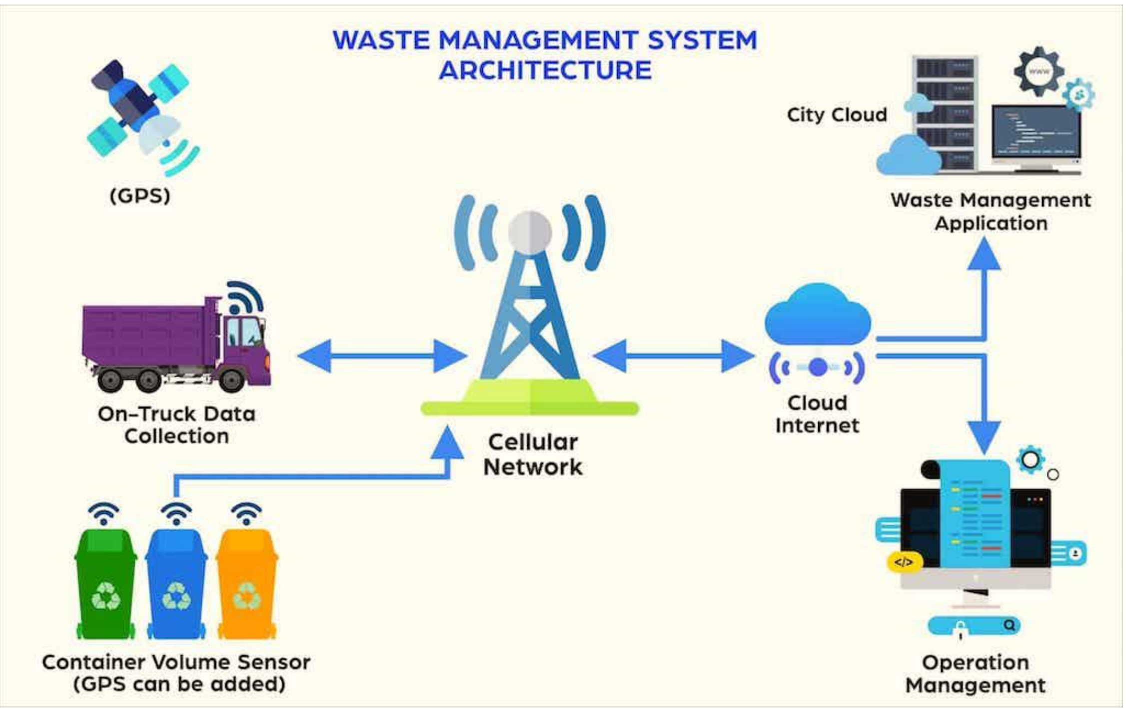
5-13. Figure_The recycling methods of LIB

[https://www.premiumtimesng.com/opinion/507777-unearthing-the-treasures-in-innovative-waste-management-by-inyene-ibanga.html?tztc=1]

6 SMART WASTE MANAGEMENT

Technology is innovating the waste management industry in many ways, turning waste into energy, creating new ways to recycle precious metals, spurring advances in route efficiency, as well as the evolution of new collection and disposal technologies.

Smart waste management refers to any system that uses technology to make trash collection and disposal more efficient, cost-effective, and environmentally friendly [[71]].



6-1. Figure_Waste Management System Architecture

[https://www.premiumtimesng.com/opinion/507777-unearthing-the-treasures-in-innovative-waste-management-by-inyene-ibanga.html?tztc=1]

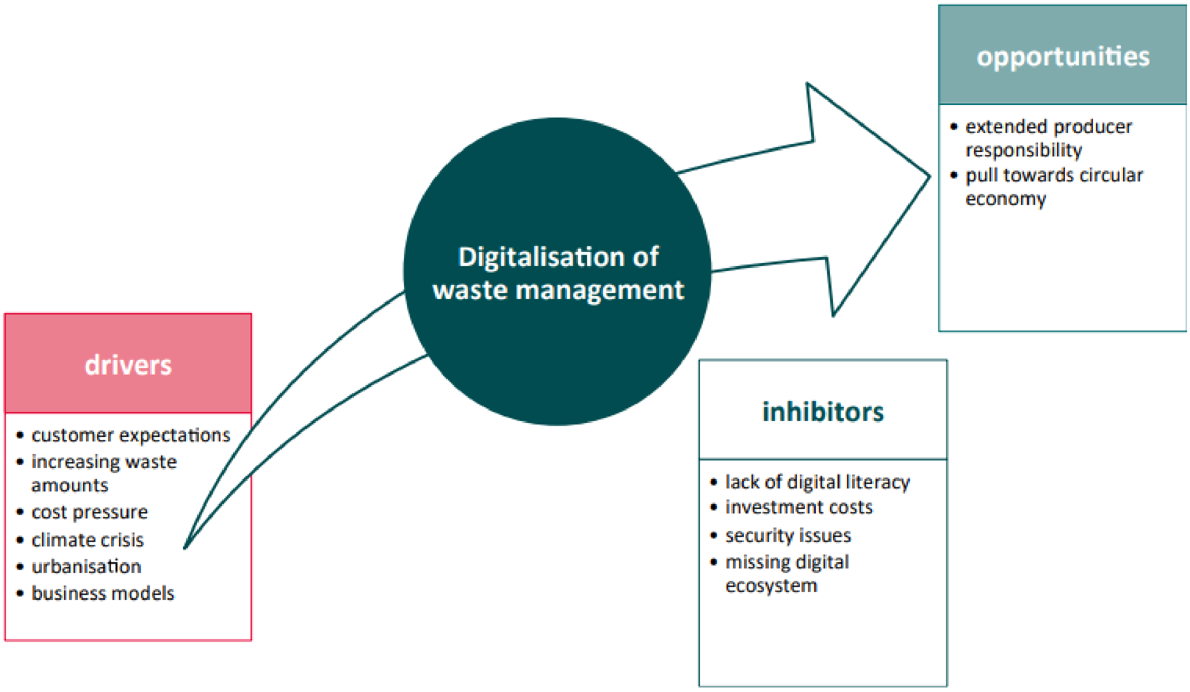
6.1 INNOVATIVE TECHNOLOGIES USED IN WASTE MANAGEMENT

Innovative technologies used in waste management include:

- ☑ Smart waste bins, waste level sensors, AI recycling/waste sorting robots, garbage truck weighing mechanisms, solar-powered trash compactors, and pneumatic waste pipes.
- ☑ Others are e-waste kiosks, recycling apps, smart fleets, and modern landfills powered by technologies that ensure environmental safety and sustainability.
- ☑ Most of these systems are equipped with the Internet of Things (IoT), a monitoring technology that collects and tracks real-time data to help optimise waste collection and disposal.

- ☑ Smart waste bins use artificial intelligence-based object recognition to automatically sort recyclables into separate compartments. The process reduces human error and helps to lower waste management costs, while also improving employee efficiency.
- ☑ Waste level sensors installed in bins or dumpsters of any size collect and store data on fill levels and help prevent public containers from overflowing and littering the surrounding environment.
- ☑ Recycling applications/platforms and e-waste kiosks are other innovations that technology has increased their efficiencies, reduced their costs, and created new opportunities for in the waste management industry.

The drivers and inhibitors for the digitalisation of waste management, with drivers being represented by opportunities and challenges are presented in 6-2. Figure.



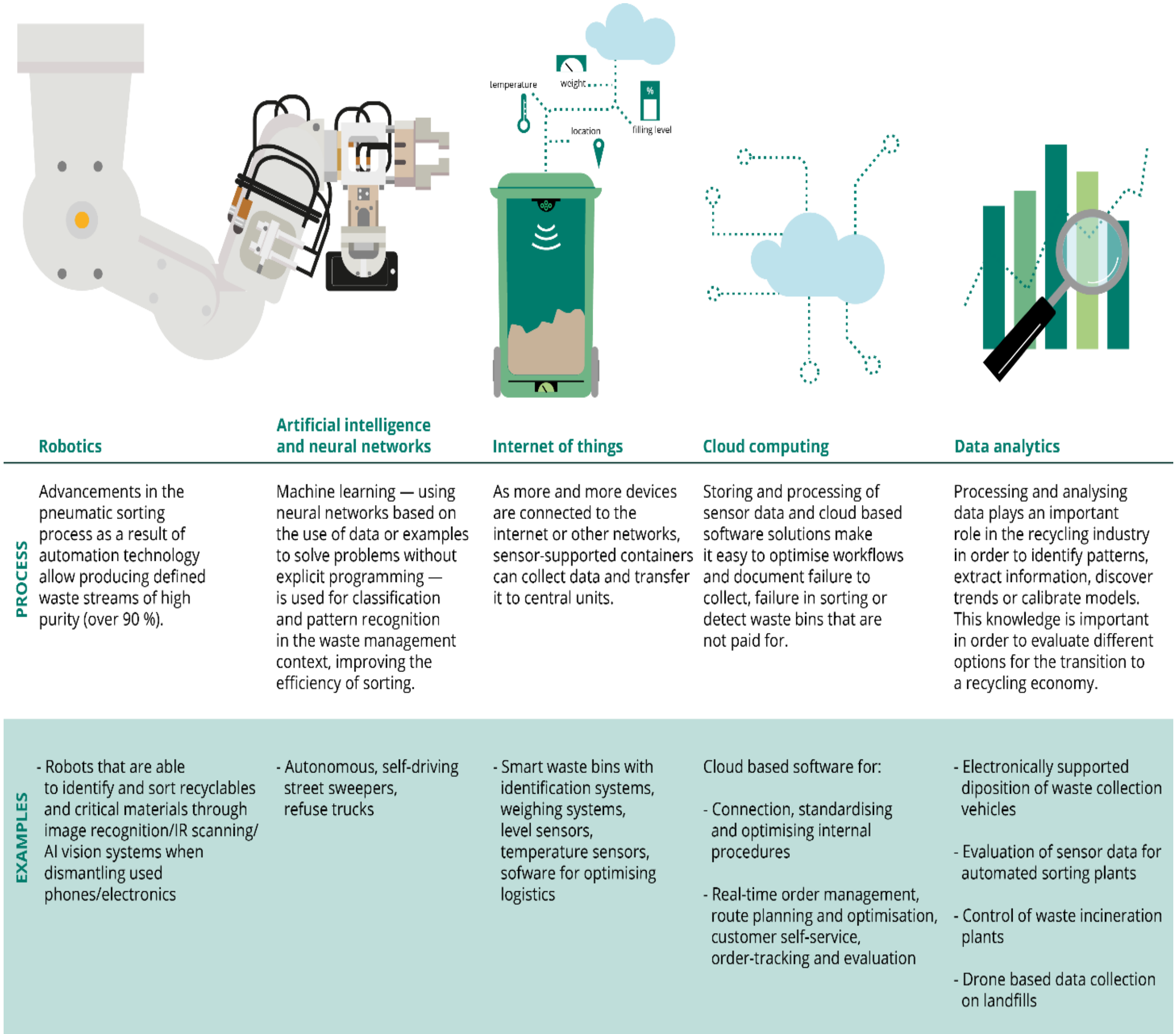
6-2. Figure_ Drivers and inhibitors for the digitalisation of waste management [72]

The problem of a dwindling workforce is being addressed with the use of AI recycling robots that accurately identify and sort recyclable materials and reduce the need for human workers.

Table 6.1_Examples of existing applications of digital technologies in waste management

Communication	Waste collection	Internal processes
Websites	Sensor equipped vehicles	Billing
Mobile apps	Route planning	Accounting
Integration in other services	Resource planning	Controlling
Third-party social media apps	Inventory tracking	Processing of orders

	Documentation	Documentation



6-3. Figure_ Use of digital technologies in waste management
https://www.eea.europa.eu/themes/waste/waste-management/digital-technologies-will-deliver-more

6.2 ROBOTIC WASTE RECYCLING SYSTEM

The robotic waste recycling system are centralized in Table 6.2.

Table 6.2_Robotic Waste Recycling System [72]

Robotic Waste Recycling System
● AI System that can be trained to sort a waste stream based on camera and Near-infrared (NIR) input data ● waste is supplied on a belt and then sorted by an x-y-z axis robotic system into different containers

● positive sorting for several fractions	
Underlying Technologies	Requirements and preconditions
● sensors ● data analytics ● AI-image classification ● robotics	● broad-band internet connection for cloud access
Benefits for waste management	Pros and Cons
The technology is able to adapt to new waste streams fast and allows for high purity sorting of this waste into multiple fractions. This improved purity leads to high-grade secondary material and less downcycling in the recycling process.	Pro ● Purity of > 90%, continuous improvement through on-the-fly training ● can pick objects up to 30 kg Con ● slow belt speed resulting in low throughput compared to established technologies (two-armed version 4000 pics/hr)
Similar applications	Development stage
● image classification is state of the art technology offered by various companies ● there are different competitors in the waste sector ● pick-and-place robots are state of the art technology for example in the food industry	● several robots running
Applicable waste streams	
● can be adapted to various items and materials ● probably most suited for construction and demolition waste	

Examples of robotics in the waste management sector [72]:

● Apple (USA): The robot Daisy dismantles up to 1.2 million used iPhones per year enabling the recycling of the used materials including tin, aluminium and cobalt which is essential for building batteries (Apple, 2020).

● BHS (USA): MAX AI is a robot that is able to identify and sort recyclables through a vision system which is continuously improved by AI (BHS, 2020).

● Remeo and Zen Robotics (Finland): Robotic waste sorting station based on image recognition and IR scanning. One robotic arm can pick more than 2,000 items per hour increasing its precision (often over 90%) in a learning process (Zen Robotics, 2020).

● Refind Industries (Sweden): Machine that sorts common batteries based on their material. Can sort up to 500 kgs per hour with a 97% precision using AI (Refind Industries, 2020).

● Autowise.ai (China), Enway (Germany): autonomous, self-driving street sweepers (Autowise.ai, 2020, ENWAY, 2020)

● Volvo Group and Renova (Sweden): autonomous, self-driving refuse truck (Volvo Group, 2020).

6.3 AI BASED SORTING TECHNOLOGY FOR PLASTIC WASTE

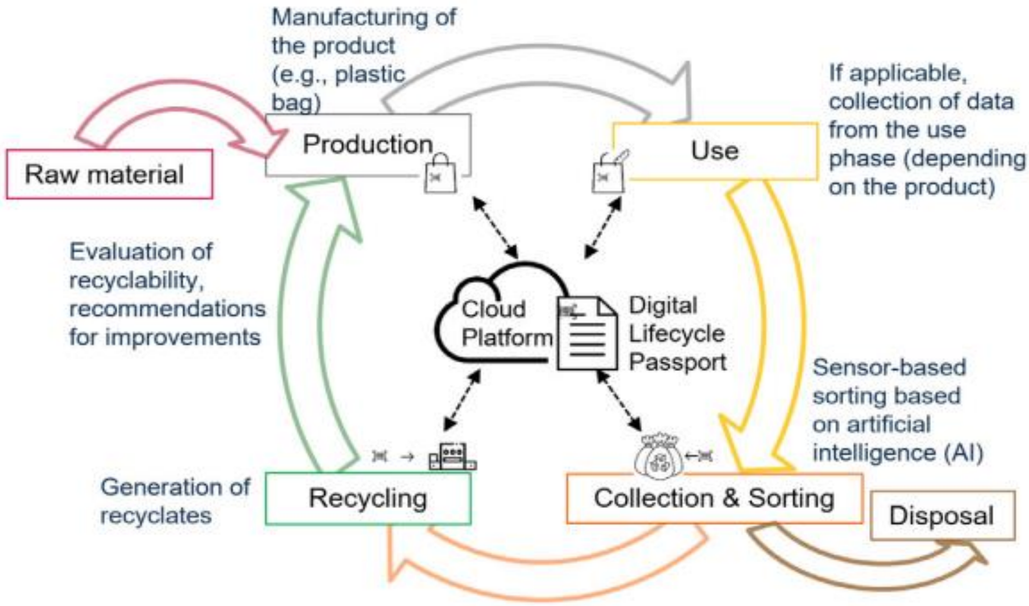
The AI based sorting technology for plastic waste is centralized in Table 6.3.

Table 6.3_ AI based sorting technology for plastic waste [72]

<table>
<tr><th colspan="2">AI based sorting technology for plastic waste</th></tr>
<tr><td colspan="2">● Add-on to existing sorting technology, plug-in in existing sorting lines
● improves sorting accuracy by providing additional features for the classification algorithm
● is trained using large amounts of sample data
● in the actual stage negative sorting of PE silicone cartridges and cartridges of 2K adhesives</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>● sensors
● data analytics
● AI-image classification
● automation</td><td>● existing sorting infrastructure as a basis for add-on
● sample Data
● incentives for high purity sorting</td></tr>
<tr><th>Benefits for circular economy</th><th>Pros and Cons</th></tr>
<tr><td>The technology allows to detect impurities that could otherwise not be detected.
The rejected substances, like silicone in PE cartridges, can have a negative effect on recyclate quality even if only low amounts are present.</td><td>Pro
● rejection of otherwise undetectable impurities
● high throughput
Con
● add-on, not replacing existing technology
● additional costs</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>● image classification as underlying technology is offered by various companies</td><td>● commercial products exist</td></tr>
<tr><th>Applicable waste streams</th><th>Sources</th></tr>
<tr><td>● currently negative sorting of plastic waste
● easy adoption to other waste streams</td><td>● company homepages</td></tr>
</table>

6.3.1 EXEMPLE: THE RECIRCE PROJECT

The **RECIRCE PROJECT** wants to improve plastic waste-sorting using artificial intelligence (AI) and then issuing a Digital Product Passport to build transparency into the recycled materials chain, making it simpler to re-use plastic granulates from complex products like electric kettles and toys [73]. The ReCircE project aims to improve the resource efficiency of material cycles by combining a digital product description – the "**life cycle** record" – with intelligent **sorting technologies supported by artificial intelligence (AI).**



6-4. Figure_ The DLCP stores information along the product lifecycle [https://doi.org/10.1016/j.procir.2022.02.021]

Information about the product and product life cycle is stored in the life cycle file. This includes, for example, the materials used in the manufacturing process and their properties. This information is made usable for material recovery – i.e. for sorting, recycling and subsequent reuse [74].

Data can be obtained from the life cycle file and used for improved sorting. Product and material data is made available to machine learning processes to enable AI-based sorting decisions. At the same time, data from sorting flows into the life cycle file and represents a further source of information for subsequent recycling processes. The data from the life cycle file as well as with the help of machine learning methods and sensor-assisted sorting can increase the overall material efficiency in the recycling of products and materials. This means that higher proportions of valuable materials can be recovered and processed into higher-quality products made from secondary raw materials.

The The ReCircE project pursues a solution approach on three levels:

- **Informational networking along the value chain**: The digital life cycle file connects producers with waste disposal companies and enables simple and efficient communication between different actors. The effects and feedback from actors' interventions are analyzed and predicted by AI. This enables producers to incorporate experiences from recycling into their product development. Disposers and recyclers, in turn, can fine-tune the sorting and recycling process if they know what the product contains.
- **Intelligent sorting and recycling of heterogeneous waste streams** : A digitalized sensor-based sorting system is used as part of the project to sort the waste. The

sorting system has sensors for color and shape recognition, near-infrared sensors and metal detectors that can be combined in any way. The sorting process is iteratively optimized based on given sensor data and the information from the digital life cycle file. For this purpose, AI decision models are created using machine learning methods that allow specific sorting rules to be generated automatically, including background information such as incompatibilities between materials. With the help of these data-based processes, the recycling process can be significantly improved.

⇨ **Resource-efficient optimization of material cycles**: The information technology integration of the data from the digital life cycle file and intelligent sorting into the assessment methodology for resource efficiency enables optimization across the entire life cycle and all relevant natural resources. In the form of a tool, different variants of product design, value chains and recycling are optimized in an integrative manner in the sense of sustainable ecological and economic control of material cycles. This should, for example, make it possible to estimate in advance which recycling, i.e. the quality level of the sorting compared to the economic and ecological effort, is suitable.

6.4 AI-BASED LITTER IDENTIFICATION

The aspects regarding AI based litter identification are centralized in Table 6.4.

Table 6.4_ AI based litter identification [72]

<table>
<tr><th colspan="2">AI-based litter identification</th></tr>
<tr><td colspan="2">● App for mobile devices that provides citizens with the possibility a picture of illegally disposed waste and report it.
● the picture and the GPS-coordinates of the littered place are submitted. An AI system classifies the pictures in order to relay it to the concerning person in charge</td></tr>
<tr><th>Underlying Technologies</th><th>Requirements and preconditions</th></tr>
<tr><td>● mobile device including camera and GPS sensor
● data analytics
● AI-image classification</td><td>● citizens using smartphones</td></tr>
<tr><th>Benefits for circular economy</th><th>Pros and Cons</th></tr>
<tr><td>The technology reduces the human labour that is needed to handle the incoming reports on illegal littering.
It serves to prepare the right removal actions beforehand.</td><td>Pro
● less human labour
● cost reduction
Con
● none</td></tr>
<tr><th>Similar applications</th><th>Development stage</th></tr>
<tr><td>● image classification is state of the art technology offered by various other companies
● the use of sensors in mobile devices is state of the art
● the combination and adaption to this specific task is not known to be offered by any other service</td><td>● in use by a German municipal service</td></tr>
<tr><th>Applicable waste streams</th><th></th></tr>
<tr><td>● illegal littering</td><td></td></tr>
</table>

6.5 AUTONOMOUS REFUSE TRUCK FOR WASTE COLLECTION

The aspects regarding autonomous refuse truck for waste collection are centralized in Table 6.5.

Table 6.5_ Autonomous refuse truck for waste collection [72]

Autonomous refuse truck for waste collection	
● reversing waste collection trucks are a major source of accidents ● in general, it is tried to avoid reversing but if necessary, the autonomous driving system can take over or support to minimize accidents and casualties ● for normal collection, skilled drivers and co-drivers are needed, but this technology allows less experienced personnel and single crewed driving ● collection personnel can walk alongside the autonomous truck when emptying bins which means less getting in and out of the truck, a potential health hazard and source of accidents	
Underlying Technologies	Requirements and preconditions
● sensors ● data analytics ● autonomous driving	● special equipped refuse truck
Benefits for circular economy	Pros and Cons
The use of autonomous driving for waste collection can be applied to overcome the labor shortage in the waste sector in some regions by reducing the necessary crew for a waste collection truck. Additionally, there might be cost benefits associated with the technology freeing up budget for other important tasks.	Pro ● potential to increase safety for the waste collection process ● lead time for bin emptying trash bin is reduced by about 30 seconds per bin because of reversing instead of normal driving ● improved fuel efficiency and less wear on truck through driving software ● data collection on traffic situations allows prediction in the future Con ● high investment costs ● legislation is not adapted to the technology so far
Similar applications	Development stage
● autonomous driving is implemented by various companies. However, only one application to the waste collection sector is known so far.	● system is being tested for 5 years ● no planned date for commercial availability ● similar technology is applied in mining trucks
Applicable waste streams	Sources
● all waste types with street side collection	● Product homepage ● ISWA Report (ISWA, 2019)

6.6 AUTOMATED VACUUM COLLECTION

The aspects regarding Automated vacuum collection are centralized in Table 6.6.

Table 6.6_ Automated vacuum collection [72]

Automated vacuum collection	
● different household waste types are collected in coloured bags at collection sites in the streets ● a subterranean tube system uses vacuum to suck the bags to a central point where they can be collected easily ● an RFID identification system coupled with a scale is used to gather real time data on the waste volumes ● the manufacturer claims that this can be used to change user behaviour and improve recycling rates	
Underlying Technologies	Requirements and preconditions
● sensors ● data analytics	● a dedicated infrastructure is needed
Benefits for circular economy	Pros and Cons
The system has the potential to lower traffic impact of waste collection and allow to design urban quarters without needing to take into account the respective demands. Possibly an improvement in waste volumes can be achieved	Pro ● easy collection at central sites ● real time data on waste volumes and types Con ● easy clogging ● difficult maintenance work ● difficult retrofitting in existing urban areas
Similar applications	Development stage
● the basic vacuum collection technology is in use in different locations ● a system including RFID identification and weighing of the waste to create real time data with the aim of changing behaviours is not known by any other manufacturer	● the underlying technology is proven - several tube-based waste collection systems exist – about 600 systems worldwide and 3 million connected people
Applicable waste streams	Sources
● household waste	● Product homepage ● ISWA Report (ISWA, 2019) ● Berg et al.

6.7 BIN SENSORS

The aspects regarding Bin sensors are centralized in Table 6.7.

Table 6.7_ Bin sensors [72]

Bin sensors	
● sensors collect vibration data from waste containers ● analysis and real-time visualisation of containers levels to improve efficiency in waste logistics ● data analysed with AI in the analytics platform	
Underlying Technologies	Requirements and preconditions
● Sensors	● broad-band internet connection for cloud

● Data analytics ● AI algorithms ● Cloud computing	access
Benefits to waste management	Pros and Cons
Improved logistics through optimisation of waste collection routes reducing unnecessary traffic, subsequently air pollution as well as associated costs.	Pro ● Energy self-sufficient ● Easy installation (attached to the container in 3 minutes) Con ● Risks of manipulation and systems failure ● Risks of data loss
Similar applications	Development stage
● Various providers exist ● In addition to the fill-level, the bin sensor collects temperature data for enabling timely reactions to incident e.g. fire-alarms if burning ● Using RFID transponders and GPS identification system, solutions can also be used for PAYT charges	● About 1000 glass containers equipped in different municipalities in Germany
Applicable waste streams	Sources
● Applicable to all types of containers ● Launched on glass containers but currently under development for additional waste streams such as textile or construction and demolition.	● Product homepage ● Berg et al.

6.8 SOFTWARE AS A SERVICE - MOBILE APPLICATION

The aspects regarding Software as a Service - Mobile application is centralized in Table 6.8.

Table 6.8_ Software as a Service - Mobile application [72]

Software as a Service - Mobile application	
● Mobile application for on-demand waste collection ● Digital marketplace (auction-like system) that puts a network of waste collectors in contact with (mostly commercial) customers (caterers, SMEs, hotels, etc.)	
Underlying Technologies	Requirements and preconditions
● Cloud computing ● Data analytics ● Automation	● Network of waste collectors
Benefits to waste management	Pros and Cons
This application aims to reduce waste collection costs for businesses (orders are made only when needed). In addition to an increased convenience for these businesses, traceability along the waste recycling value chain is facilitated. The revenues of recovered materials are shared with the commercial waste generators. This could also be	Pro ● Reduction of collection costs by reducing the number of pick-up ● Facilitate customers sustainability reporting Con ● Competition between current waste collectors and independent local haulers

an incentive for improving the quality of waste collected.	
Similar applications	Development stage
● Apps exist that enable customers to promptly order waste collection services, and interact with waste operators online. Similarly, another solution allows commercial businesses from different sectors – such as construction, the automobile industry, or food retail – to make individual requests and compare various offers of various waste disposers.	● Network of 5 000 waste collection businesses ● Expanding beyond US, for instance partnering with European firms
Applicable waste streams	Sources
● Mainly commercial waste	● Open Resource, 2017 ● Company Homepages

6.9 SOFTWARE AS A SERVICE - INTELLIGENT WASTE TRANSPORT OPTIMISATION

The issues regarding Software as a Service - Intelligent Waste Transport Optimisation are presented summary in Table 6.9.

Table 6.9_ Software as a Service - Intelligent Waste Transport Optimisation [72]

Software as a Service - Intelligent Waste Transport Optimisation	
● Real time-based automatic scheduling for waste transport planning optimisation ● The solution encompasses fleet management, route planning and optimisation and routing services and is delivered as an integrated part of the service provider's platform or connects to third party ERP systems. ● The master routes are planned and optimised in the route planning system based on recurring customer visits. The master routes are then automatically transferred to the Fleet Planner, with which both the operational planning and the actual implementation are managed.	
Underlying Technologies	Requirements and preconditions
● Cloud computing ● Sensors ● AI ● Data analytics	● Customer fleet of vehicles ● Customer's involvement for generating data
Benefits to waste management	Pros and Cons
Increased efficiency in waste collection operations, reduction in number of vehicles needed reducing associated transport emissions.	Pro ● Customer cost savings and better services ● Decrease in time spent on planning and administration Con ● /
Similar applications	Development stage
Various provider exist	● Implemented solution. Responsible for collection, administration and deposits for 2,700 stores around Sweden, for instance implemented for optimizing the transportation planning of deposit-refund systems for cans and bottles.
Applicable waste streams	Sources
● All waste types	● company homepage; ● ISWA Report (ISWA, 2019)

6.10 THE CIRCULAR DIGITAL ECONOMY LAB - DIGITIZATION AND ROBOT ASSISTED PROCESSES USABLE FOR RECYCLING

The Circular Digital Economy Lab (CDEL) is a development and demonstration laboratory to explore technical-economic approaches to circular economy for issues and needs of the SME sector, making digitization and robot-assisted processes usable for recycling [[75]].

In this context, circular economy means the extensive recycling of materials so that their value is retained. By linking information and process technology competencies, supplemented by business management know-how, innovative potentials are developed cooperatively.

The core of the CDEL is a modular, networked, digitized dismantling and recycling line that can be flexibly adapted to different products. In this process, end-of-life products are automatically detected, disassembled as optimally as possible, effectively separated into residual materials and fed to new production routes. The findings from this are used for improved product design.

The CDEL dismantling and recycling line consists of different devices and systems that can be flexibly adapted to different products:

- industrial robot
- X-ray technology
- water jet cutting technology
- sorting and conveying systems
- mills
- image processing and sensors
- measuring technology
- muffle furnace
- vacuum melting furnace
- Additive manufacturing
- Analytics (GCMS, ICP, XRF).

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