Module 6

Introduction to environmental challenges and waste in the automotive industry

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Waste reduction management

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ACRONYMS

ACEA European Automobile Manufacturers' Association

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

GLOSSARY OF TERMS USED

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

For the purposes of the Directive 2000/53/EC with subsequent amendments and rectifications (Current consolidated version: 30/03/2023):

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;

11. '**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 TO DIRECTIVE 2008/98/EC

For the purposes of Directive 2008/98/EC on waste and repealing certain Directives (Current consolidated version: 05/07/2018), 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 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: 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

Waste management in the automotive industry is a consequence of the dynamic development of this industry and must cover the aspects of sustainable logistics, ecological and environmental safety. The main objective of waste management is to reduce the amount of unusable materials and prevent potential health hazards and environment.

The production of automobiles in the global automotive sector is increasing, which causes an increase in the amount of waste, an increase in energy consumption and an increase in harmful emissions. Thus, the sustainable management of automotive waste as well as a program to minimize it are needed as an indispensable specialty in the global automotive industry. Automotive waste is a worldwide concern, so manufacturers involved in the automotive industry agree to the Auto Waste Minimization Program to reduce the environmental impact of the manufacturing process while recycling and reusing end-of-life vehicles.

Automobiles are classified as the most recyclable engineering products, offering recovery rates of up to 90%. Typically, a commercial machine includes 65% steel, about 7 – 8% aluminum, with some reusable materials such as copper, plastic, rubber and copper.

The concept of waste management incorporates several approaches to turning waste into profitable items, using strategies such as the "circular economy". This is the most comprehensive strategy that automakers use to recycle automotive waste and improve their profit margins by recovering end-of-life materials and products.

Nowadays, car companies adopt efficient waste recycling methods and use materials that maintain their quality until the end of the extraction process. Closed loop recycling is the most impactful approach used whereby a product is enabled for self-recycling. By organizing an automotive waste minimization program, professionals proactively collect end-user vehicles from end-users. This method of recycling automotive waste reduces energy consumption by 75% and thus helps in significant cost savings in the downstream manufacturing process.

Automakers are now proactive rather than reactive. Starting from manufacturing processes, waste management initiatives have been extended to supply chains, non-manufacturing faculties, product performance and final disposal.

In addition, the fundamentals also include the ability to establish supply chains with professionalism, with high levels of operational efficiency, along with societal and environmental efficiency.

The course provides students with:

- familiarization with the latest technologies for the recovery and storage of materials and their recycling.

- knowledge of the law in the management of technological waste of various types (also dangerous), as well as of machines taken out of use.

- knowledge of end-of-life vs end-of-waste concepts.

- understanding the transition from the policy of waste management to the policy of resource management, with the respect in practice of the hierarchy of solutions for circularity (extending the life of products through reinvention/repurposing, the second-hand market, repair, reuse of components and, only as a last step, recycle).

1 THE EUROPEAN ENVIRONMENTAL REGULATORY FRAMEWORK

Worldwide regulatory framework is pushing new design methods and practices for environmental purposes. Since the Maastricht Treaty was signed on 7 February 1992, institutions and regulatory methods are changing in environmental rule making within European Union.

The firms are getting more and more involved in the regulatory process and the European automakers are not only establishing their own environmental policies but also acting as responsible for the implementation of a programme that depends both on suppliers and partners.

Regarding the recycling regulations, the French automakers were pioneers in Europe in promoting voluntary agreements between all firms involved and the government. A so-called “l’Accord Cadre” was signed in 1993. This agreement set up goals such as: at 2002 all vehicles produced should be 95% recyclable. On these proposes the French Companies Peugeot, Citroën and Renault have been working together on assembling and “disassembling” technical specifications and materials identifications reaching separation for recycling. It means that recycling criteria has to be integrated into all other functional requirements of the vehicle project. They also have to share this task, and the risks, with their suppliers, comprising the R&D expenses [[1]].

The regulatory framework has a great power of diffusion concerning global products such as vehicles. Furthermore, increasing recyclability rate is also connected to the new system of Environmental Management Systems – EMS – largely regulated by ISO 14000 and other national standards systems of environmental quality.

1.1 DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL OF 19 NOVEMBER 2008 ON WASTE AND REPEALING CERTAIN DIRECTIVES (TEXT WITH EEA RELEVANCE)

This Directive 2008/98/EC lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use [[2]].

1.1.1 DISPOSAL OPERATIONS ACCORDING TO DIRECTIVE 2008/98/EC ON WASTE

Disposal operations according to Directive 2008/98/EC on Waste, Annex I

D 1	Deposit into or on to land (e.g. landfill, etc.)
D 2	Land treatment (e.g. biodegradation of liquid or sludgy discards in soils, etc.)
D 3	Deep injection (e.g. injection of pumpable discards into wells, salt domes or naturally occurring repositories, etc.)
D 4	Surface impoundment (e.g. placement of liquid or sludgy discards into pits, ponds

	or lagoons, etc.)
D 5	Specially engineered landfill (e.g. placement into lined discrete cells which are capped and isolated from one another and the environment, etc.)
D 6	Release into a water body except seas/oceans
D 7	Release to seas/oceans including sea-bed insertion
D 8	Biological treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 12
D 9	Physico-chemical treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 12 (e.g. evaporation, drying, calcination, etc.)
D 10	Incineration on land
D 11	Incineration at sea (1)
D 12	Permanent storage (e.g. emplacement of containers in a mine, etc.)
D 13	Blending or mixing prior to submission to any of the operations numbered D 1 to D 12 (2)
D 14	Repackaging prior to submission to any of the operations numbered D 1 to D 13
D 15	Storage pending any of the operations numbered D 1 to D 14 (excluding temporary storage, pending collection, on the site where the waste is produced) (3)
(1) This operation is prohibited by EU legislation and international conventions. (2) If there is no other D code appropriate, this can include preliminary operations prior to disposal including pre-processing such as, inter alia, sorting, crushing, compacting, pelletising, drying, shredding, conditioning or separating prior to submission to any of the operations numbered D1 to D12. (3) Temporary storage means preliminary storage according to point (10) of Article 3.	

1.1.2 RECOVERY OPERATIONS ACCORDING TO DIRECTIVE 2008/98/EC ON WASTE

Recovery operations according to Directive 2008/98/EC on waste, Annex II

R 1	Use principally as a fuel or other means to generate energy (1)
R 2	Solvent reclamation/regeneration
R 3	Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes) (2)
R 4	Recycling/reclamation of metals and metal compounds
R 5	Recycling/reclamation of other inorganic materials (3)
R 6	Regeneration of acids or bases
R 7	Recovery of components used for pollution abatement
R 8	Recovery of components from catalysts
R 9	Oil re-refining or other reuses of oil
R 10	Land treatment resulting in benefit to agriculture or ecological improvement
R 11	Use of waste obtained from any of the operations numbered R 1 to R 10
R 12	Exchange of waste for submission to any of the operations numbered R 1 to R 11 (4)
R 13	Storage of waste pending any of the operations numbered R 1 to R 12 (excluding temporary storage, pending collection, on the site where the waste is produced) (5)
(1) This includes incineration facilities dedicated to the processing of municipal solid waste only where their energy efficiency is equal to or above: — 0,60 for installations in operation and permitted in accordance with applicable Community legislation before 1 January 2009, — 0,65 for installations permitted after 31 December 2008, using the following formula: Energy efficiency = (Ep - (Ef + Ei))/(0,97 × (Ew + Ef))	

In which:

Ep means annual energy produced as heat or electricity. It is calculated with energy in the form of electricity being multiplied by 2,6 and heat produced for commercial use multiplied by 1,1 (GJ/year)

Ef means annual energy input to the system from fuels contributing to the production of steam (GJ/year)

Ew means annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year)

Ei means annual energy imported excluding Ew and Ef (GJ/year)

0,97 is a factor accounting for energy losses due to bottom ash and radiation.

This formula shall be applied in accordance with the reference document on Best Available Techniques for waste incineration.

(2) This includes gasification and pyrolisis using the components as chemicals.

(3) This includes soil cleaning resulting in recovery of the soil and recycling of inorganic construction materials.

(4) If there is no other R code appropriate, this can include preliminary operations prior to recovery including pre-processing such as, inter alia, dismantling, sorting, crushing, compacting, pelletising, drying, shredding, conditioning, repackaging, separating, blending or mixing prior to submission to any of the operations numbered R1 to R11.

(5) Temporary storage means preliminary storage according to point (10) of Article 3.

1.1.3 PROPERTIES OF WASTE WHICH RENDER IT HAZARDOUS ACCORDING TO DIRECTIVE 2008/98/EC ON WASTE

Properties of waste which render it hazardous according to Directive 2008/98/EC on Waste, Annex III

H 1	'Explosive': substances and preparations which may explode under the effect of flame or which are more sensitive to shocks or friction than dinitrobenzene.
H 2	'Oxidizing': substances and preparations which exhibit highly exothermic reactions when in contact with other substances, particularly flammable substances.
H 3-A	'Highly flammable' —liquid substances and preparations having a flash point below 21 °C (including extremely flammable liquids), or —substances and preparations which may become hot and finally catch fire in contact with air at ambient temperature without any application of energy, or —solid substances and preparations which may readily catch fire after brief contact with a source of ignition and which continue to burn or to be consumed after removal of the source of ignition, or —gaseous substances and preparations which are flammable in air at normal pressure, or —substances and preparations which, in contact with water or damp air, evolve highly flammable gases in dangerous quantities.
H 3-B	'Flammable': liquid substances and preparations having a flash point equal to or greater than 21 °C and less than or equal to 55 °C.
H 4	'Irritant': non-corrosive substances and preparations which, through

	immediate, prolonged or repeated contact with the skin or mucous membrane, can cause inflammation.
H 5	'Harmful': substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may involve limited health risks.
H 6	'Toxic': substances and preparations (including very toxic substances and preparations) which, if they are inhaled or ingested or if they penetrate the skin, may involve serious, acute or chronic health risks and even death.
H 7	'Carcinogenic': substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce cancer or increase its incidence.
H 8	'Corrosive': substances and preparations which may destroy living tissue on contact.
H 9	'Infectious': substances and preparations containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organisms.
H 10	'Toxic for reproduction': substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce non-hereditary congenital malformations or increase their incidence.
H 11	'Mutagenic': substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce hereditary genetic defects or increase their incidence.
H 12	Waste which releases toxic or very toxic gases in contact with water, air or an acid.
H 13 (1)	'Sensitizing': substances and preparations which, if they are inhaled or if they penetrate the skin, are capable of eliciting a reaction of hypersensitization such that on further exposure to the substance or preparation, characteristic adverse effects are produced.
H 14	'Ecotoxic': waste which presents or may present immediate or delayed risks for one or more sectors of the environment.
H 15	Waste capable by any means, after disposal, of yielding another substance, e.g. a leachate, which possesses any of the characteristics listed above.

Notes

Attribution of the hazardous properties 'toxic' (and 'very toxic'), 'harmful', 'corrosive', 'irritant', 'carcinogenic', 'toxic to reproduction', 'mutagenic' and 'eco-toxic' is made on the basis of the criteria laid down by Annex VI, to Council Directive 67/548/EEC of 27 June 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances (2).

2. Where relevant the limit values listed in Annex II and III to Directive 1999/45/EC of the European Parliament and of the Council of 31 May 1999 concerning the approximation of the laws, regulations and administrative provisions of the Member States relating to the classification, packaging and labelling of dangerous preparations (3) shall apply.

Test methods

The methods to be used are described in Annex V to Directive 67/548/EEC and in other relevant CEN-notes.

(1) As far as testing methods are available.

(2) OJ 196, 16.8.1967, p. 1.

(3) OJ L 200, 30.7.1999, p. 1.

1.1.4 WASTE PREVENTION MEASURES ACCORDING TO DIRECTIVE 2008/98/EC ON WASTE

Waste prevention measures referred to in article 29 according to DIRECTIVE 2008/98/EC ON WASTE, ANNEX IV:

MEASURES THAT CAN AFFECT THE FRAMEWORK CONDITIONS RELATED TO THE GENERATION OF WASTE

1. The use of planning measures, or other economic instruments promoting the efficient use of resources.
2. The promotion of research and development into the area of achieving cleaner and less wasteful products and technologies and the dissemination and use of the results of such research and development.
3. The development of effective and meaningful indicators of the environmental pressures associated with the generation of waste aimed at contributing to the prevention of waste generation at all levels, from product comparisons at Community level through action by local authorities to national measures.

MEASURES THAT CAN AFFECT THE DESIGN AND PRODUCTION AND DISTRIBUTION PHASE

1. The promotion of eco-design (the systematic integration of environmental aspects into product design with the aim to improve the environmental performance of the product throughout its whole life cycle).
2. The provision of information on waste prevention techniques with a view to facilitating the implementation of best available techniques by industry.

3. Organise training of competent authorities as regards the insertion of waste prevention requirements in permits under this Directive and Directive 96/61/EC.
4. The inclusion of measures to prevent waste production at installations not falling under Directive 96/61/EC. Where appropriate, such measures could include waste prevention assessments or plans.
5. The use of awareness campaigns or the provision of financial, decision making or other support to businesses. Such measures are likely to be particularly effective where they are aimed at, and adapted to, small and medium sized enterprises and work through established business networks.
6. The use of voluntary agreements, consumer/producer panels or sectoral negotiations in order that the relevant businesses or industrial sectors set their own waste prevention plans or objectives or correct wasteful products or packaging.
7. The promotion of creditable environmental management systems, including EMAS and ISO 14001.

MEASURES THAT CAN AFFECT THE CONSUMPTION AND USE PHASE

1. Economic instruments such as incentives for clean purchases or the institution of an obligatory payment by consumers for a given article or element of packaging that would otherwise be provided free of charge.
2. The use of awareness campaigns and information provision directed at the general public or a specific set of consumers.
3. The promotion of creditable eco-labels.
4. Agreements with industry, such as the use of product panels such as those being carried out within the framework of Integrated Product Policies or with retailers on the availability of waste prevention information and products with a lower environmental impact.
5. In the context of public and corporate procurement, the integration of environmental and waste prevention criteria into calls for tenders and contracts, in line with the Handbook on environmental public procurement published by the Commission on 29 October 2004.
6. The promotion of the reuse and/or repair of appropriate discarded products or of their components, notably through the use of educational, economic, logistic or other measures such as support to or establishment of accredited repair and reuse-centres and networks especially in densely populated regions.

1.2 ELV DIRECTIVE 2000/53/EC

The **ELV DIRECTIVE 2000/53/EC** [[3]] of the European Parliament and of the Council of European Union on End-of-life Vehicles adopted by European Union members in October 2000 is the state of art of a negotiation process, between interested parties, and public authorities that has lasted for a decade already.

The directive states that for reuse and recovery purposes that preference to recycling must be given to the recovery of components, which cannot be reused when environmental viable recycling process is available, without prejudice to requirements regarding the safety of vehicles and environmental other requirements such as air emissions and noise control.

This means that for car industry recyclability does not assure sustainability.

Sustainability claims for protection of human health and ecology, clean technologies (at both levels: production and recycling), enforced environmental legislation, well-organised collection systems and large market assuring secondary materials supply and demand for recycled materials. For these purposes automotive industry is supposed to be responsible for their products (vehicles or auto parts) from cradle to grave. That means that they have to close automotive materials life cycle loop reducing the existent ones and even avoiding extra environmental impacts.

It sets out measures to prevent and limit waste from end-of-life vehicles (ELVs) and their components by ensuring their reuse, recycling and recovery. It also aims to improve the environmental performance of all economic operators involved in the life-cycle of the vehicles.

KEY POINTS

- Vehicle and equipment manufacturers must factor in the dismantling, reuse and recovery of the vehicles when designing and producing their products. They have to ensure that new vehicles are: reusable and/or recyclable to a minimum of 85% by weight per vehicle; reusable and/or recoverable to a minimum of 95% by weight per vehicle.

- They cannot use hazardous substances such as lead, mercury, cadmium and hexavalent chromium.

- Manufacturers, importers and distributors must provide systems to collect ELVs and, where technically feasible, used parts from repaired passenger cars.

- Owners of ELVs delivered for waste treatment must receive a certificate of destruction, necessary to deregister the vehicle.

- Manufacturers must meet all, or a significant part, of the costs involved in the delivery of an ELV to a waste treatment facility. For a vehicle owner, they should incur no expenses when delivering an ELV to an authorised waste treatment facility, except in the rare cases where the engine is missing or the ELV is full of waste.

- Waste treatment facilities must apply for a permit or register with the competent authorities of the EU country where they are located.

- ELVs are first stripped before further treatment takes place. Hazardous substances and components are removed and separated. Attention is given to the potential reuse, recovery or recycling of the waste.

- Clear quantified targets for annual reporting to the European Commission exist for the reuse, recycling and recovery of ELVs and their respective parts. These have become increasingly more demanding.

- This legislation applies to passenger vehicles and small trucks but not to big trucks, vintage vehicles, special-use vehicles and motorcycles.

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**.

DIRECTIVE (EU) 2018/849 [4] amends Directive 2000/53/EC giving the Commission the power to adopt:

- implementing acts concerning the detailed rules necessary to control EU countries' compliance with the ELV targets and the exports and imports of ELVs;

- delegated acts to supplement the directive by:

- exempting certain materials and components containing lead, mercury, cadmium or hexavalent chromium (other than in cases listed in Annex II), if their use is unavoidable and establishing maximum concentration levels allowed as well as deleting materials and components of vehicles from Annex II, if their use is avoidable,

- introducing coding standards to facilitate the components suitable for reuse and recovery,

- establishing the minimum requirements for the certificates of destruction,

- establishing minimum requirements for the treatment of ELV.

The recent evaluation of the existing EU legislation regulating the area - 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 ("3R type-approval Directive", adopted in 2005) - has shown that considerable improvements were needed to boost the transition of the automotive sector to a circular economy, thereby reducing the environmental impact linked to the production and end-of-life treatment of vehicles, and strengthening the sustainability of the automotive and recycling industry in Europe.

A review of the ELV Directive was launched in 2021, resulting in a proposal for a new regulation in July 2023 [5].

The European Commission is proposing measures to enhance the circularity of the automotive sector, covering the design, production and end-of-life treatment of vehicles. This initiative will improve access to resources for the EU's economy, contribute to the EU's environmental and climate objectives, while reinforcing the single market and contributing to address the challenges associated with the ongoing transformation of the automotive industry.

The proposed actions are expected to generate €1.8 billion net revenue by 2035, with additional jobs created and enhanced revenue streams for the waste management and recycling industry, and, also, will contribute to better road safety in third countries by preventing the export of non-roadworthy vehicles and reducing harmful pollution and health risks in countries importing used vehicles from the EU.

The proposed regulation, replacing the current Directives on end-of-life vehicles and on reusability, recyclability and recoverability, is expected to have substantial environmental benefits, including an annual reduction of 12.3 million tons of CO2 emissions by 2035, better valorisation of 5.4 million tons of materials, and increased recovery of critical raw materials.

The implementation of the regulation will lead to long-term energy savings at the manufacturing stage, reduced dependency on imported raw materials, and the promotion of sustainable and circular business models.

ACTIONS FOR CIRCULAR TRANSITION AND MORE RESILIENCE IN AUTOMOTIVE SECTOR

It is projected that automotive sector will become the largest consumer of critical raw materials used in permanent magnets of e-drive motors in Europe. Enhancing the EU's resilience against supply chain disruptions and reducing its dependency on critical raw materials imports is key to the transition to zero-emission vehicles.

To facilitate the sector's transition, the Commission has revised the existing legislation and proposes a single regulation that focuses on several key elements to improve quality in design, collection, and recycling, while facilitating reporting obligations:

'DESIGN CIRCULAR': Enhancing circularity in the design and production of vehicles will help to ensure these can be easily dismantled. Car makers will need to provide clear, detailed instructions for dismantlers on how to replace and remove parts and components during use and end-of-life stage of a vehicle.

'USE RECYCLED CONTENT': 25% of the plastic used to build a new vehicle will be required to come from recycling, of which 25% must be recycled from end-of-life vehicles.

‘TREAT BETTER': The measures will lead to recovering more and better-quality raw materials, including critical raw materials, plastics, steel and aluminium. 30% of plastics from end-of-life vehicles should be recycled. Additional measures will support the market for reuse, remanufacturing and refurbishment of parts and components of a vehicle. Member States are encouraged to provide incentives to garages and repair shops to support the sale of spare parts.

'IMPROVE GOVERNANCE': The new rules will reinforce producer responsibility by establishing national Extended Producer Responsibility schemes under uniform requirements. These schemes will aim to provide proper financing for mandatory waste treatment operations, incentivise recyclers in improving quality of recycled materials from end-of-life vehicles, thus fostering enhanced cooperation between treatment operators and manufacturers.

‘COLLECT MORE AND SMARTER': To put a stop to vehicles disappearing, the proposal foresees better enforcement of the current rules and increases transparency. This means more inspections, digital tracking of end-of-life vehicles across the EU, better separation of old cars from end-of-life cars, more fines for infringements, and a ban on exporting used vehicles that are not roadworthy.

'COVER MORE VEHICLES': The scope of these measures will be gradually expanded to include new categories such as motorcycles, lorries, and buses, ensuring a more comprehensive coverage.

1.3 DIRECTIVE 2006/66/EC ON BATTERIES AND ACCUMULATORS AND WASTE BATTERIES

DIRECTIVE ON BATTERIES AND ACCUMULATORS AND WASTE BATTERIES

In European countries, the placement in the market of batteries and accumulators, including their collection and end-of-life recycling, is currently regulated by **DIRECTIVE 2006/66/EC** [[6]]. According to this directive, Member States must implement every necessary measure to promote and optimise separate collection, preventing these products from being disposed of as mixed municipal waste.

This led to the set-up of pick-up points close to users, allowing them to drop off the used batteries and accumulators for pick-up by manufacturers free of charge.

However, due to the exponential increase of electric vehicles powered by batteries that are growing more and more advanced and complex in technology, this directive (which applies to all types of batteries, regardless of their chemistry and end use) has become obsolete. It is unfit for today's technological developments and has not kept pace to adequately regulate the recovery and disposal of latest-generation accumulators.

This is why it has become necessary to replace it with a new regulation suited to the upward trend in battery demand and more aligned with the climate neutrality objectives the EC is pursuing.

THE NEW EUROPEAN BATTERY REGULATION

The European Union has set a new important objective for the next decades: to boost the circular economy, the sustainability of products and processes, and the support of Europe's technological progress in the battery sector. To this end, it has decided to introduce the new so-called EU Battery Regulation and give a clear direction towards a regulatory framework for batteries in Europe that can ensure sustainability of the entire value chain over the long term.

In July 2023 the European Council adopted a new regulation that strengthens sustainability rules for batteries and waste batteries, that will regulate the entire life cycle of batteries – from production to reuse and recycling – and ensure that they are safe, sustainable and competitive [[7]]. The regulation of the European Parliament and the Council will apply to all batteries including all waste portable batteries, electric vehicle batteries, industrial batteries, starting, lightning and ignition (SLI) batteries (used mostly for vehicles and machinery) and batteries for light means of transport (e.g. electric bikes, e-mopeds, e-scooters).

The new rules aim to promote a circular economy by regulating batteries throughout their life cycle. The regulation establishes end-of-life requirements, including collection targets and obligations, targets for the recovery of materials and extended producer responsibility:

- ☑ sets targets for producers to collect waste portable batteries (63% by the end of 2027 and 73% by the end of 2030), and introduces a dedicated collection objective for waste batteries for light means of transport (51% by the end of 2028 and 61% by the end of 2031).
- ☑ sets a target for lithium recovery from waste batteries of 50% by the end of 2027 and 80% by the end of 2031, which can be amended through delegated acts depending on market and technological developments and the availability of lithium.
- ☑ provides for mandatory minimum levels of recycled content for industrial, SLI batteries and EV batteries. These are initially set at 16% for cobalt, 85% for lead, 6% for lithium and 6% for nickel. Batteries will have to hold a recycled content documentation.
- ☑ sets the recycling efficiency target for nickel-cadmium batteries at 80% by the end of 2025 and 50% by the end 2025 for other waste batteries.
- ☑ provides that by 2027 portable batteries incorporated into appliances should be removable and replaceable by the end-user, leaving sufficient time for operators to adapt the design of their products to this requirement. This is an important provision for consumers. Light means of transport batteries will need to be replaceable by an independent professional.

1.4 WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT (WEEE) DIRECTIVE

Applied since August 2012, and incorporated into national laws in February 2014, the Directive is designed to prevent WEEE, creating ground for the recovery, reuse and recycling of produce. After not achieving the expected results, the legislation was modified in 2016, increasing the collection of electronic waste from 4 kg of annual waste per inhabitant, to a national target of 45% of the annual weight. In 2019 the target increase to 65%. The Directive places responsibility on producers to cover the costs of collecting, treating and -sustainable disposing of waste at determined collection areas.

1.5 EUROPEAN FRAMEWORK ON THE CIRCULAR ECONOMY

1.5.1 EUROPEAN REGULATIONS ON THE CIRCULAR ECONOMY

The goal of transitioning to a circular economy has gained significant importance among policymakers worldwide, including in Europe. The circular economy aims to decouple economic growth from resource consumption by emphasizing resource efficiency, waste reduction, and the reuse and recycling of materials. To facilitate this transition, the European Union (EU) has implemented a comprehensive array of regulations and directives.

European regulations on the circular economy encompass several overarching objectives. Firstly, they strive to stimulate sustainable economic growth by promoting resource efficiency and waste reduction. By embracing a circular economy, Europe aims to enhance its competitiveness, foster job creation, and minimize its environmental footprint.

Secondly, these regulations aim to encourage innovation and the development of sustainable business models. The EU recognizes the potential for industries to innovate and capitalize on the increasing demand for sustainable products and services within the circular economy framework.

Lastly, European regulations on the circular economy target the sustainable use of resources, reduction of greenhouse gas emissions, and mitigation of the environmental impacts associated with resource extraction, production, and waste disposal. By optimizing material usage throughout their lifecycle, these regulations aim to minimize Europe's ecological footprint.

Key Features of European Regulations on the Circular Economy:

- **WASTE MANAGEMENT AND RECYCLING TARGETS**: The EU has established ambitious targets for waste management and recycling to drive the transition towards a circular economy. The Waste Framework Directive sets a goal of recycling 65% of municipal waste and 75% of packaging waste by 2030. Additionally, the directive promotes separate waste collection, waste prevention measures, and the implementation of extended producer responsibility schemes.
- **ECODESIGN AND PRODUCT STANDARDS**: European regulations also prioritize improving the environmental performance of products. The Ecodesign Directive mandates product-specific requirements to ensure energy efficiency, recyclability, and durability. These requirements incentivize manufacturers to design products with longer lifespans, easier repairability, and increased recyclability.
- **EXTENDED PRODUCER RESPONSIBILITY (EPR):** EPR is a fundamental principle of the circular economy that shifts the environmental responsibility of products to manufacturers. The EU has introduced EPR schemes for various products, including electronics, batteries, packaging, and vehicles. Manufacturers are obliged to take responsibility for the collection, recycling, and safe disposal of their products at the end of their life.
- **SINGLE-USE PLASTICS DIRECTIVE**: To combat the pervasive issue of plastic pollution, the EU implemented the Single-Use Plastics Directive. This directive prohibits certain single-use plastic items, such as cutlery and straws, and sets recycling targets for plastic bottles. It also encourages the use of alternative materials and emphasizes producer responsibility for plastic waste.
- **CIRCULAR ECONOMY ACTION PLAN**: The Circular Economy Action Plan, devised by the European Commission, provides a comprehensive roadmap for the transition to a circular economy. It includes measures to promote sustainable product design, support circular business models, enhance waste management and recycling practices, and encourage sustainable consumption.

1.5.2 THE CIRCULAR ECONOMY ACTION PLAN

The EU's Circular Economy Action Plan was a comprehensive body of legislative and non-legislative actions adopted in 2015, which aimed to transition the European economy from a linear to a circular model. The Action Plan mapped out 54 actions, as well as four legislative proposals on waste. These legislative proposals were put forward by the European Commission along with the Action Plan and included targets for landfill, reuse, and recycling, to be met by 2030 and 2035, along with new obligations for separate collection of textile and biowaste. The Action Plan covered several policy areas, material flows, and sectors alongside cross-cutting measures to support this systemic change through innovation and investments, and also announced a sectoral strategy for plastics. More than EUR 10 billion of public funding was allocated to the transition between 2016 and 2020 [[8]].

On 11 March 2020, the European Commission adopted a new Circular Economy Action Plan [[9]], one of the main building blocks of the European Green Deal [[10]], Europe's new sustainable growth agenda. The new action plan provides the measures throughout the product life cycle and aims to prepare European economy for a green future, strengthen competitiveness, while protecting the environment and give new rights to consumers. The new Circular Economy Action Plan paves the way for a competitive, climate-neutral economy in which consumers are held accountable.

The Circular Economy Action Plan, part of the EU Industrial Strategy [[11]], presents measures to:

- **MAKE SUSTAINABLE PRODUCTS THE NORM IN THE EU**. The Commission will propose legislation on Sustainable Product Policy, to ensure that products placed on the EU market are designed to last longer, are easier to reuse, repair and recycle, and incorporate as much as possible recycled material instead of primary raw material. Single-use will be restricted, premature obsolescence tackled and the destruction of unsold durable goods banned.
- **EMPOWER CONSUMERS.** Consumers will have access to reliable information on issues such as the reparability and durability of products to help them make environmentally sustainable choices. Consumers will benefit from a true 'Right to Repair'.
- **FOCUS ON THE SECTORS THAT USE THE MOST RESOURCES AND WHERE THE POTENTIAL FOR CIRCULARITY IS HIGH.** The Commission will launch concrete actions on:
    - **electronics and ICT** – a 'Circular Electronics Initiative' to have longer product lifetimes, and improve the collection and treatment of waste
    - **BATTERIES AND VEHICLES –** new regulatory framework for batteries for enhancing the sustainability and boosting the circular potential of batteries
    - **packaging –** new mandatory requirements on what is allowed on the EU market, including the reduction of (over)packaging

- **plastics** – new mandatory requirements for recycled content and special attention on microplastics as well as biobased and biodegradable plastics
- **textiles** – a new EU Strategy for Textiles to strengthen competitiveness and innovation in the sector and boost the EU market for textile reuse
- **construction and buildings** – a comprehensive Strategy for a Sustainably Built Environment promoting circularity principles for buildings
- **food** – new legislative initiative on reuse to substitute single-use packaging, tableware and cutlery by reusable products in food services

- **ENSURE LESS WASTE.** The focus will be on avoiding waste altogether and transforming it into high-quality secondary resources that benefit from a well-functioning market for secondary raw materials. The Commission will explore setting an EU-wide, harmonised model for the separate collection of waste and labelling.The Action Plan also puts forward a series of actions to minimise EU exports of waste and tackle illegal shipments.

In February 2021, European Parliament adopted a resolution on this plan calling for further measures to achieve a fully circular, carbon-neutral, sustainable and toxic-free economy by 2050. Stricter recycling rules and mandatory targets for the consumption of raw materials by 2030 are also required.

In March 2022, the Commission presented a first package of measures to accelerate the transition to a circular economy under the Circular Economy Action Plan. Proposals include promoting sustainable products, encouraging consumers for the green transition, reviewing building materials regulations and a strategy for sustainable textiles.

1.6 THE CIRCULAR CARS INITIATIVE - WORLD ECONOMIC FORUM

The Circular Cars Initiative (CCI) is a private/public sector collaboration focused on leveraging new technologies and business models to align the automotive industry with a 1.5C climate scenario. Through an integrated systems approach, CCI will provide a platform for actors in the value chain to eliminate gaps between economic incentives and social outcomes. A core goal of CCI is to leverage sectoral knowledge, partnerships, funding and creativity to help community members develop technologies and business models to eliminate emissions from automotive utilization and manufacturing [[12]].

The global automotive industry confronts a profound moment of transition. Today the automotive ecosystem is an engine for prosperity, but it’s also a major driver for environmental degradation. On an annualized basis, the industry produces more greenhouse gas emissions than the entire European Union and roughly 20% of these emissions are directly attributable to manufacturing. While the shift towards battery electric vehicles will decrease use-phase emissions substantially, in the short term it will also increase manufacturing emissions. This is due to the large carbon footprint of EV batteries. Under a business as usual scenario, by 2040 McKInsey & Co analysis for the Circular Cars Initiative estimates roughly 60% of total automotive lifecycle emissions will be directly attributable to materials – with just 40% coming from other sources including logistics, end of life disposal and utilization. Any clear path toward a 1.5C climate scenario will require significant and aggressive decarbonization of these non-use phase emissions.

THE CIRCULAR CARS INITIATIVE (CCI) is a partnership between stakeholders from the automobility ecosystem (e.g. industry, policymakers and fleet purchasers) to eliminate or minimize total lifecycle emissions with a special emphasis on manufacturing emissions. The initiative's overarching goal is to achieve an automobility system that is convenient, affordable and firmly grounded within a 1.5°C climate scenario by 2030.

The term **"CIRCULAR CAR"** refers to a theoretical vehicle that has maximized materials efficiency. This notional vehicle would produce zero materials waste and zero pollution during manufacture, utilization and disposal – which differentiates it from today's zero emission vehicles. While cars may never be fully "circular," the automotive industry can significantly increase its degree of circularity. Doing so has the potential to deliver economic, societal and ecological dividends.

In present, half the cost of producing a new vehicle comes from manufactured materials. At end of life, little of this value is recoverable due to non-circular design practices and the lack of circularity-focused business models. Just as vehicles consume non-renewable fuel, producing atmospheric pollution and GHG emissions as atmospheric waste, they also consume vast quantities of currently non-renewable materials that result in massive quantities of liquid and solid waste. These are generally landfilled, processed or downcycled at end of life.

Inefficient utilization of cars is also a problem. Privately-owned vehicles are only in use about 5% of the time, and even then, they tend to operate at low passenger capacity.

All this points toward significant opportunities for innovation and improved materials efficiency – both in manufacturing and utilization. Over the coming decade, to remain competitive, global automotive companies must embrace change and the imperatives of sustainability and climate change. The pathway toward mobility with both zero emissions and zero environmental waste will inevitably include increased reliance on circular cars and economics.

CCI aims to virtually eliminate automobility emissions by targeting what we call "materials efficiency." This key measurement of "materials efficiency" is still in the process of formalized definition. But one simple formula is the quantity of raw materials used to build a vehicle divided by the number of passenger miles provided by that vehicle. Other quantifiable metrics, such as recycled content, or GHG emissions/passenger km may also be included.

One early goal of CCI will be to define "materials efficiency" with respect to key metrics and end goals (e.g. GHG emissions, rare earth elements utilization, etc.) in collaboration with industry stakeholders and regulators. CCI aims to develop appropriate frameworks for measuring materials efficiency and drastically improve the industry's performance with regard to these metrics – thus reducing the automobile's lifecycle environmental footprint and at the same time significantly increasing the vehicle's full life-cycle value. CCI will also generate industry transition tools that point toward the most effective and economic decarbonization pathways.

Some of the strategies for increasing the materials efficiency of automobiles under examination include: implementing new business models like pooled mobility as a service (MaaS); closed loop recycling of aluminium and steel; and life extension of vehicles and key components such as batteries.

CCI will incubate circularity-focused pilots with members of the CCI community and collaborate to catalyse the development of new markets and materials networks necessary to achieve circularity [[13]].

MANUFACTURERS have significantly improved the resource efficiency of their production processes and products, and want to reduce their environmental impact even more in the future. Each year, Europe's automobile sector spends €60.9 billion on innovation, making the industry the EU's number one investor in R&D. These investments range from reducing the carbon footprint of the production phase to improving the design of motor vehicles in order to allow for their efficient repair.

Auto manufacturers are already actively contributing to resource efficiency by remanufacturing a wide variety of parts, including engines and gear-boxes. In practice, remanufactured components have proven to reduce energy consumption during manufacturing by up to 80% when compared to new parts. Giving components a new life also requires 88% less water and more than 90% less chemicals. This circular approach can reduce overall waste by an impressive 70%.

The automobile industry does not only contribute to the circular economy by remanufacturing components or reducing waste, but also by prolonging the service life of the vehicles it produces. Manufactures have a responsibility to their customers to support the longevity of vehicles by ensuring that they can be serviced, repaired and maintained. Extending the lifetime of a vehicle is essential to reducing costs for consumers, as well as conserving natural resources and energy.

Finally, manufacturers remain dedicated to further improving fuel efficiency and reducing CO_2 emissions, as the use phase of a vehicle still accounts for a large part of the total environmental impact that cars have. Because of the industry's commitment to the 'design for sustainability' concept, vehicles are built to be as sustainable as possible over their entire lifecycle. From prolonging the in-use phase of passenger cars and commercial vehicles to recyclability at the end of their life, the sector focusses its efforts on reducing the overall environmental impact in those areas that matter most.

Besides industry-led initiatives, automobile manufacturers also have to adhere to a wide range of existing legislation promoting sustainable production, more efficient vehicles and their proper dismantling. The End-of-Life Vehicles Directive, for example, already sets a target of 95% recyclability per vehicle per year. As a result of economic incentives, as well as existing legislation, the automotive industry has made the circular economy an integral part of its DNA.

ENVIRONMENTAL PROTECTION is one of the basic pillars of the carmaker's sustainability and the automotive industry has the opportunity to shape this fundamental restructuring. When devising strategies and business models, companies should not only consider direct product purchasers but all users and groups affected by transport issues. The automobile changed from a technical to a social commodity: it guarantees the personal mobility and social participation, shapes the cities and landscapes, and structures the temporal and spatial thinking. This is why it have to rethink the whole automotive industry – with the focus on the use rather than the production of vehicles, in order to make the lives of individual users more enjoyable, more efficient and safer.

Environmental strategic visions and plans of automotive companies are generally based on the following key objectives [14]: non-waste production technologies; reduction of emissions throughout the life cycle; reduction in fuel consumption and alternative sources of propulsion; replacement of non-recyclable materials; reducing the consumption of energy and water in the production process.

Even the actual production processes are more sophisticated, the environmental impacts are formed in the following three main stages: inputs, operations, products [15].

In actual context of the automotive industry, ***circular economy are part of four strategic ways:***

- ☑ decarbonising energy usage,
- ☑ establishing circular material flows,
- ☑ extending and optimising product lifetime and
- ☑ improving capacity utilisation during vehicle usage.

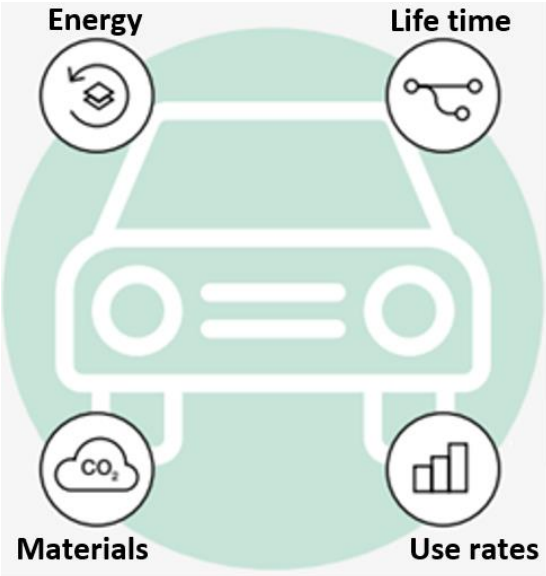
Producers such as Renault, Volvo, PSA, Daimler, BMW, Volkswagen have already set ambitious targets towards carbon neutrality and aligned their business strategies with an ever-accelerating push for electrifying their products [16].

Original equipment manufacturers are heavily investing in electrification, closing material loops, and developing new service offerings and mobility solutions. investors and regulators are pushing to go further.

Cars are increasingly bought online and flexibly subscribed to for shorter time periods, revenue streams are shifting towards the use phase and the drive towards circularity is slowly picking up speed. Already most automotive materials are recyclable. cars are built to last and to be repaired. These are all important aspects of circularity. The value chain needs to be fundamentally reimagined to minimise lifetime carbon emissions and resource consumption.

THE "CIRCULAR CAR", as a strategic concept, adopts a circular flow in the whole product lifecycle: reduction, recovery, repair, renovation, reuse, and recycling of all components. These processes are a part of the value chain, and the reason is to increase value and the circularity of materials. A circular car maximizes value to society, the environment and the economy while efficiently using resources and public goods. Its value is measured in terms of its ability to provide mobility, and its efficiency is measured in terms of carbon emissions, non-circular resource consumption and use of public goods, such as space or clean air [17].

The definition focuses on the relevant variables [18]: energy, materials, lifetime, and use (1-1. Figure). **ENERGY** is used efficiently (per km of movement) and renewable; **LIFETIME** of the vehicle and components is optimized for resource efficiency (by emphasizing efficient design, modularity, purpose-built vehicles, reuse, repair, remanufacturing, etc.). **MATERIALS** are used without waste (reduced, reused, recycled and/or renewed). **USE RATES** are optimized (accounting for resiliency requirements).

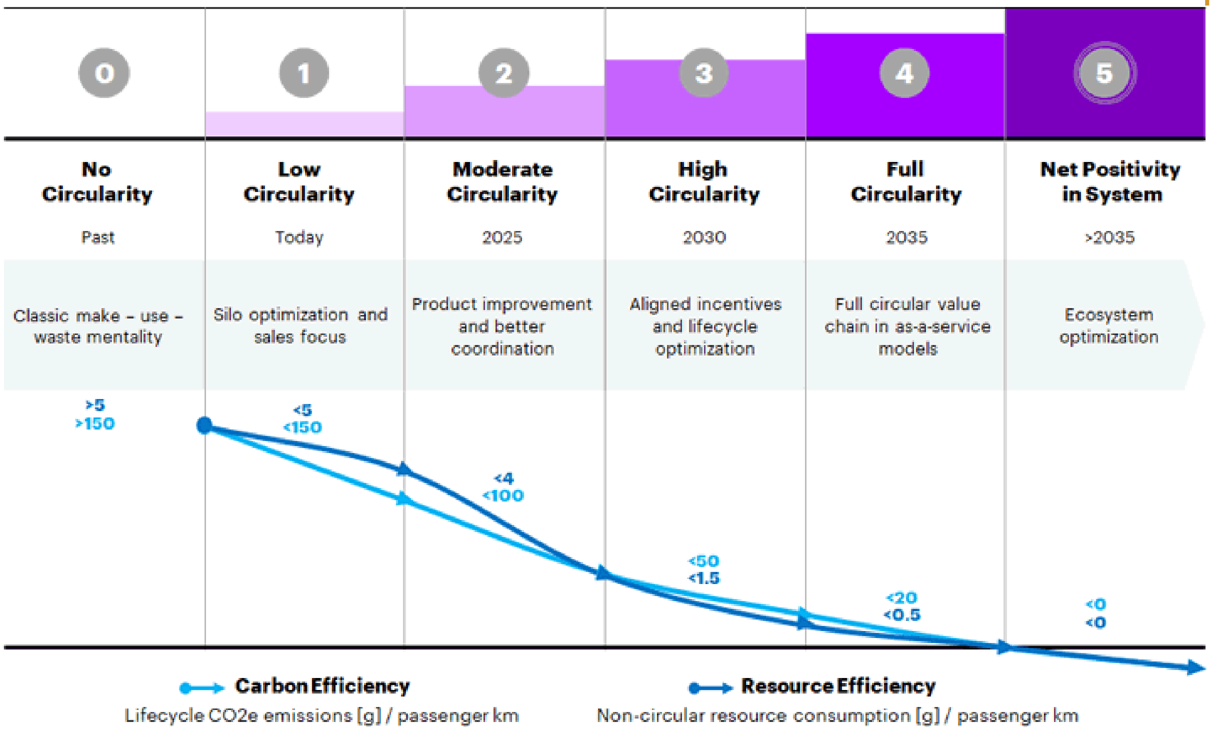


1-1. Figure_ The circular economy value chain for automotive companies

[https://www3.weforum.org/docs/WEF_A_policy_research_agenda_for_automotive_circularity_2020.pdf]

Accenture proposes a taxonomy with **FIVE LEVELS OF CIRCULARITY** based on two primary measures (carbon and resource efficiency) to evaluate and improve the circularity of cars [19]. The proposed levels range from single owner use and disposal (Level 0) to an aspirational goal of an automobility ecosystem that has net positive impacts (Level 5).

The levels describe vehicles that are part of an increasingly circular automobility system. Each level can be determined based on the characteristics of both the product and its use, so the producer and the owner of the car are responsible for achieving circularity.



1-2. Figure_Five levels of automotive circularity

[Source: WEF & Accenture, Raising Ambitions: A new roadmap for the automotive circular economy, 2020]

1.7 ENVIRONMENTAL MANAGEMENT SYSTEMS

1.7.1 ISO 14000: ENVIRONMENTAL MANAGEMENT STANDARDS

The ISO 14000 Environmental Management Standards are a family of standards. They define how companies and organizations manage their environmental responsibilities.

The following standards belong, as the numbers indicate, to this family. LCA software and any Environmental Management Software should comply with these standards.

ISO 14001: Environmental Management System: ISO 14001 defines the criteria Environmental Management Systems have to comply with. It ensures that environmental impacts are being measured and improved.

ISO 14021: Environmental Claims and Labels: ISO 14021 defines how specific environmental claims have to be and how they have to be formulated and documented.

ISO 14040:2006: Life Cycle Assessment Framework: ISO 14040:2006 defined the principles and framework of a Life Cycle Assessment. Many parts of this article are based on ISO 14040:2006.

ISO 14044: The Update: ISO 14044 replaced earlier versions of ISO 14041 to ISO 14043.

ISO 14067: Quantifying carbon footprint: ISO 14067 defines how the carbon footprint of products is quantified during a Life Cycle Assessment.

ISO 50001: Efficient Energy Management: ISO 50001 defines Energy Management Systems.

1.7.2 ECO-MANAGEMENT AND AUDIT SCHEME (EMAS)

EMAS is the European environmental management tool designed to support organizations in the continuous improvement of environmental performance integrating the concept of sustainable development.

Environmental management systems (EMS) means “an organizational change within corporations and an internally motivated effort at environmental self-regulation by adopting management practices that integrate the environment into production decisions, identifying opportunities for pollution and waste reductions, and implementing plans to make continuous improvements in production methods and environmental performance”. ESM may also include: environmental reporting, environmental performance monitoring, and performance evaluation.

Currently, among the environmental management systems, the most important are the standards of the International Standards Organization (ISO 14001) and the European Union Environmental Management and Auditing Scheme (EMAS).

The main difference of the ISO with respect to the EMAS was that it was freely available, meaning that any organization, regardless of its profile, that wanted to embrace pro environmental activities could apply for certification; since EMAS II came into force, the difference between the two schemes is only formal.

1.7.3 ISO 22628:2002 ROAD VEHICLES — RECYCLABILITY AND RECOVERABILITY — CALCULATION METHOD

End-of-life road vehicles contribute to the total volume of waste to be treated. As part of the road vehicle life cycle, it is essential that recovery issues be taken into consideration **DURING THE DESIGN PHASE** for environmentally sound treatment to be ensured.

Today, recycling has to be taken into account in addition to safety, emissions and fuel consumption when designing a road vehicle. Consequently, there is need for an indicator for evaluating the ability and potential of new vehicles to be recovered/recycled.

The method for calculating recyclability and recoverability rates specified by this International Standard is based on four main stages inspired by the treatment of end-of-life road vehicles. Recyclability/recoverability rates depend on the design and material properties of new vehicles, and on the consideration of proven technologies — those technologies which have been successfully tested, at least on a laboratory scale, in this context.

The calculation method of this International Standard cannot reflect the process that will be applied to the road vehicle at the end of its life.

The International Standard ISO 22628:2002 specifies a method for calculating the recyclability rate and the recoverability rate of a **NEW ROAD VEHICLE**, each expressed as a percentage by mass (mass fraction in percent) of the road vehicle, which can potentially be

— recycled, reused or both (recyclability rate), or

— recovered, reused or both (recoverability rate).

The calculation is performed by the vehicle manufacturer when a new vehicle is put on the market.

2 WASTE MANAGEMENT AND REDUCTION IN AUTOMOTIVE INDUSTRY

2.1 WASTE MANAGEMENT FRAMEWORK

Waste management can be generally considered the entire treatment or handling process from waste collection via recycling/treatment to final disposal. Although the concept of close-loop or green supply chain has been introduced and discussed for approximately two decades, it is still a long way to go to achieve holistic green supply chain management due to the extremely high costs and technical requirements. Sustainable waste management can be considered as the first step for achieving holistic green supply chain management [[20]].
According to Directive 2008/98/EC **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.

ENVIRONMENTAL ASPECTS OF THE AUTOMOTIVE INDUSTRY

- Emissions
- Noise reduction
- Mobile air-conditioning systems (MACs)
- Diesel cars.

MANAGEMENT

- planning waste management activities
- training of staff involved in waste management
- organizing the waste management activity
- evaluation of activities in the waste management process
- pursuing and fulfilling the responsibilities regarding the waste management

WASTE MANAGEMENT refers to the various schemes to manage and dispose of wastes. It can be by discarding, destroying, processing, recycling, reusing, or controlling wastes. The prime objective of waste management is to reduce the amount of unusable materials and to avert potential health and environmental hazards.

Waste management is associated with the manufacturing process of all products. The most recommended waste management approaches include the reduction of the quantity of generated waste, the expansion of environmentally friendly recycling technologies, and the maximization of re-use while at the same time fulfilling governmental measures related to waste management [[21]].

Waste management is one of the main challenges faced by more advanced societies given the steady increase in its production and environmental, economic and social impact.

Despite the fact that this is the environmentally least sustainable option, most of this waste continues to be disposed of in landfill sites.

However, the current trend is to reduce this practice in favor of environmentally and economically more interesting options. The Waste Framework Directive of 2008 introduced a waste management hierarchy in which the indicated options from higher to lower priority are prevention, reuse, recycling, material and energy recovery and, finally, disposal of the waste. As would be expected, the first option is based on **REDUCING WASTE GENERATION** either by discouraging the sale of disposable articles, limiting the use of plastics, encouraging the return of glass packaging, etc.

The second best option is **REUSE**, which can be undertaken depending on the specific product concerned (packaging, toner cartridges, shopping bags, clothing, etc.). Although the product itself may occasionally not be able to be reused, it can nevertheless be recycled for another use, such as the case of paper and glass.

If none of these alternatives are feasible, and rather than simply depositing waste in a landfill site, the only sustainable means of gaining some economic benefit from it is to recover the valuable products from it.

RECOVERY can be either material or energy-based.

- ⇨ Material recovery involves using the waste as a raw material in another process. This is the case of slag from blast furnaces and the rubble produced during building demolitions etc., which can be used in cement production as they contain the same minerals present in the traditional raw materials.
- ⇨ Energy recovery is another means of extracting some benefit from waste by using it to obtain renewable energy while solving an environmental problem.

The various energy recovery technologies available can be classified as either biological or thermal processes. The former can be applied when the waste contains a significant biodegradable fraction, whereas the latter will be viable when the calorific value of the waste, which is measured by way of the lower calorific value (LCV), is medium or high.

Most widely used **ENERGY RECOVERY PROCESSES** are:

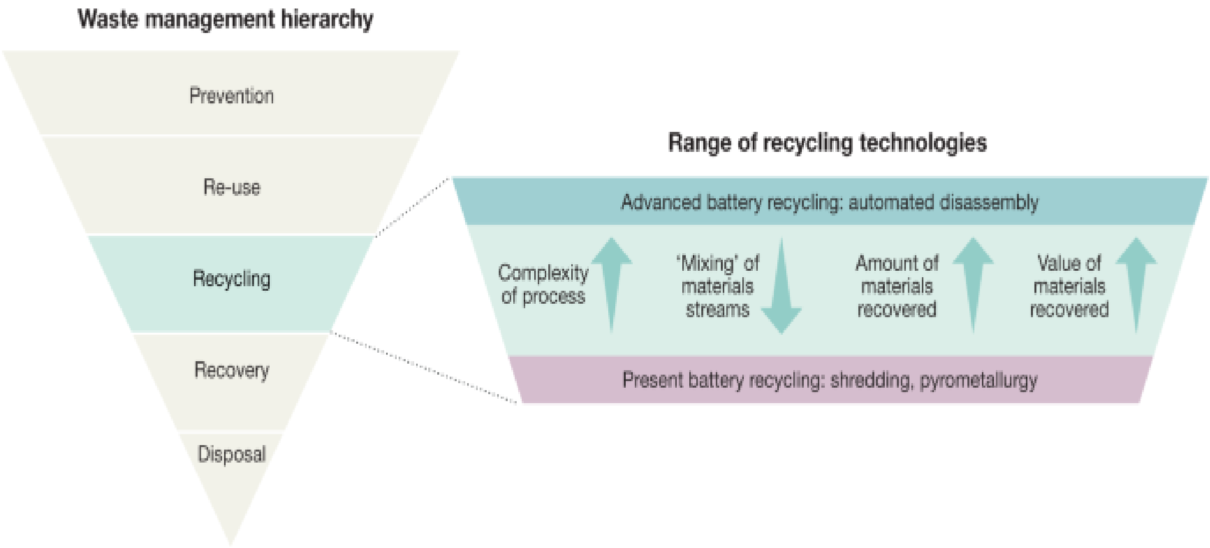
- ⇨ Disposal and exploitation of landfill gas
- ⇨ Biomethanization
- ⇨ Pyrolysis
- ⇨ Gasification
- ⇨ Combustion with excess oxygen (incineration).

2.2 WASTE-MANAGEMENT HIERARCHY AND CIRCULAR ECONOMY

The End-of -Life Vehicles (ELV) Directive was introduced to ensure that the waste produced by recycling older vehicles was maintained at sustainable levels. Primarily, car recycling should not only help to remove and store potential toxins from ELVs, it should also breathe new life into used car parts that can continue to be used on other vehicles.

The aim of current European Union waste management directives is to promote prevention of waste and the application of a waste management hierarchy: preparing for reuse, recycling, other recovery, and disposal.

The following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy [22]: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g. energy recovery; and (e) disposal



2-1. Figure_Waste management hierarchy for EV battery [23]

The Waste Framework Directive only measures the waste operations recycling, incineration, and landfill individually, not measuring the implementation of the waste hierarchy principle in Member States of the European Union.

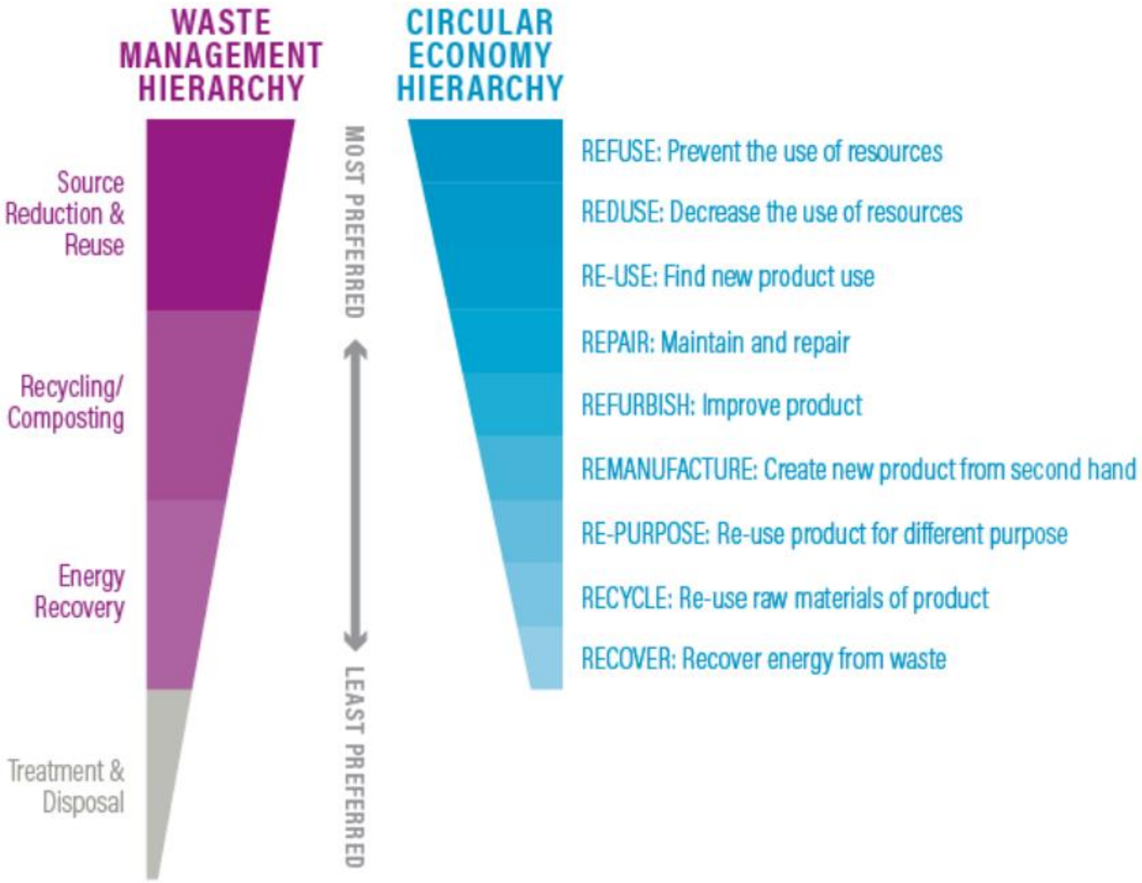
Recent studies propose a Waste Hierarchy Index (WHI) to measure waste hierarchy in the context of the circular economy, applied to municipal solid waste [24]. In the development of the WHI, recycling and preparation for re-use, as defined by Eurostat, were considered as positive contributors to the circular economy, and incineration and landfill as negative factors.

The WHI has been applied at different geographic scales (local and national level) to verify its potential and limitations. The WHI is a straightforward and concise indicator that provides a holistic view of how waste is managed.

The WHI is more than a source of waste statistics; it is the beginning of a real discussion about how waste statistics should be managed to reach a circular economy by implementing the waste hierarchy.

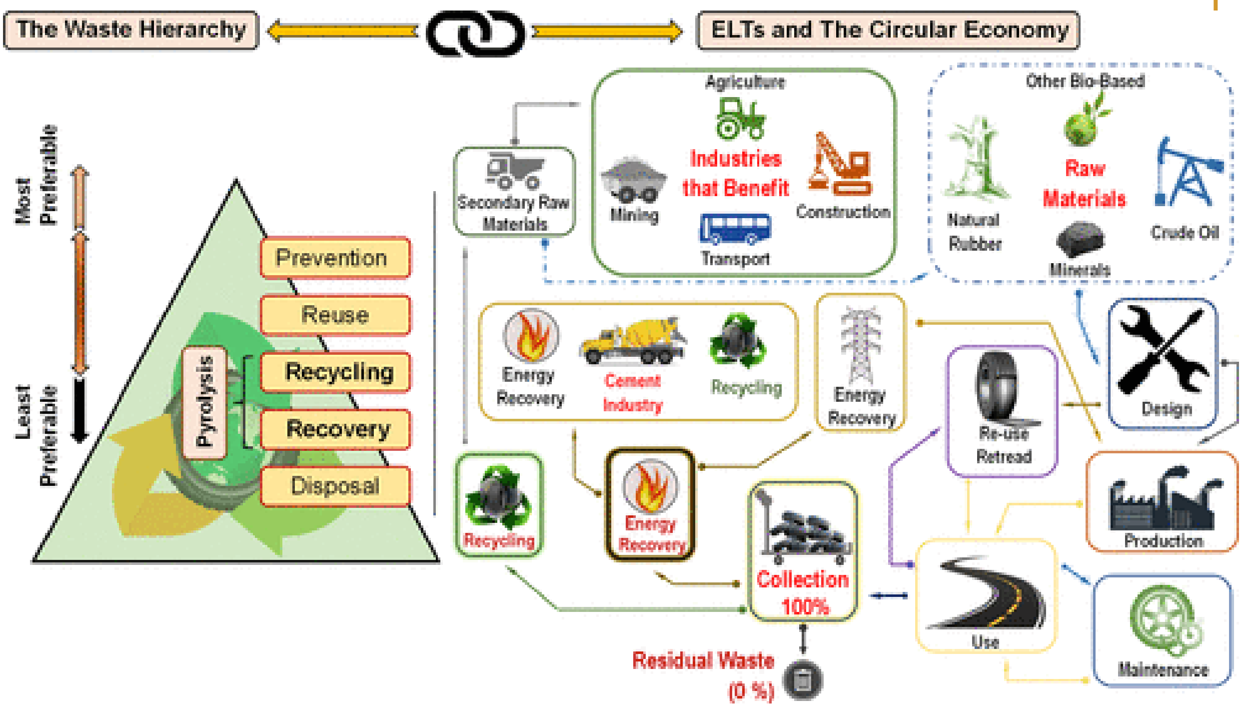
CIRCULAR ECONOMY MODEL The waste challenge posed by EV batteries combined with the rapidly increasing demand for raw materials creates a significant opportunity to develop a circular economy.

The following figure outlines the necessary business activities and their importance in creating a circular economy. Applying this framework to EV batteries, the top priorities will be preventing and decreasing the use of resources (particularly rare earth metals) and finding new uses for batteries removed from electric vehicles.



2-2. Figure_Necessary business activities and their importance in creating a circular economy

Source: WRI Center of Expertise on Resources



2-3. Figure_ ELTs management within the circular economy approach [https://doi.org/10.1021/acs.energyfuels.3c00847]

2.3 WASTE REDUCTION FRAMEWORK

WASTE REDUCTION, also known as source reduction, is the practice of using less material and energy to minimize waste generation and preserve natural resources.

Waste reduction is broader in scope than recycling and incorporates ways to prevent materials from ending up as waste before they reach the recycling stage.

Waste reduction includes reusing products such as plastic and glass containers, purchasing more durable products, and using reusable products, such as dishrags instead of paper towels.

Purchasing products that replace hazardous materials with biodegradable ingredients reduces pollution as well as waste.

In general, waste reduction offers several environmental benefits. Greater efficiency in the production and use of products means less energy consumption, resulting in less pollution. More natural resources are preserved. Products using less hazardous materials are used. Finally, less solid waste ends up in landfills.

Waste reduction also means economic savings. Fewer materials and less energy is used when waste-reduction practices are applied. Rather than using the traditional cradle-to-grave approach, a cradle-to-cradle system is adopted.

In this cradle-to-cradle system, also called industrial ecology, products are not used for a finite length of time. Instead of disposing of materials, or the components of a product after a single use, products are passed on for further uses. This is considered a flow of materials. This can be applied within an organization, or between organizations that may be considered unrelated, on a cooperative basis.

Waste can be reduced by individuals, businesses, institutions such as hospitals or educational facilities, organizations, municipalities, or government agencies.

2.4 WASTE REDUCTION IN AUTOMOTIVE COMPANIES

Manufacturers can establish product recycling, refurbishment, and replacement programs which engage with customers directly. By increasing the points of customer contact, firms have more opportunities to improve customer engagement, brand loyalty, and the profit margins [[25]].

This strategy focuses on designing vehicle components to be recyclable, reusable, and remanufacturable from the outset.

Integrating these concepts into product design and initial manufacturing is critical to reducing remanufacturing costs later on in the product cycle. Although it does require additional R&D investment today, it will reap benefits in the future in the form of lower production costs.

Lengthening product usability after a ‘rent instead of sell’ model has been implemented will serve to improve firm profitability even further – as vehicle repair expenses decrease in the face of constant recurring revenue streams paid by customers.

Opportunities for improving material usability include ensuring that the materials used are adequately suitable for a closed-loop manufacturing system, investing in R&D to further improve on the recyclability of engines, as well as leveraging new 3D printing technologies when producing smaller-batch niche components.

BENEFITS OF REDUCING WASTE

Improving waste management can benefit business and the environment by:

- ☑ reducing the cost of purchasing metals and other raw materials through process improvements (e.g. fewer offcuts and rejects)
- ☑ minimising waste treatment and disposal costs
- ☑ reducing environmental impacts associated with waste disposal and consumption of limited resources (e.g. by reviewing purchasing practices or testing the suitability of recycled or non-composite materials that can be separated and recycled if they meet customer specifications and requirements)
- ☑ improving the reputation of business and employee satisfaction through promoting an environmentally responsible image and providing a safer and more comfortable workplace.

2.4.1 MAJOR WASTE GENERATING ACTIVITIES

The major environmental wastes generated by the automotive manufacturing industry include: machine lubricants and coolants; aqueous and solvent cleaning systems; paint; and scrap metals and plastics.

Hazardous cleaning chemicals are very common and are likely to require special waste management arrangements. Office and warehousing wastes, such as paper, printer cartridges, pallets and packaging materials can also be avoided, reused or recycled [26].

IMPLEMENTING WASTE MANAGEMENT IMPROVEMENTS may require forward planning and some changes to the way in business operates.

For example:

- ☑ proposed changes may need to be discussed with managers, workplace safety representatives, unions, insurers, investors, suppliers and customers to identify possible risks to quality, productivity, work conditions or security and check that they are acceptable (e.g. protect products from damage during shipment and delivery if surplus packaging is removed and check that customers will accept products without packaging);
- ☑ employee training and awareness may be required to successfully implement actions and support the introduction of new equipment or processes, such as changes to quality management procedures, use of on-site wastewater and other recycling systems, or sorting of waste streams;
- ☑ special licences or permits may be required by the business or contractors to store, treat, transport or dispose of hazardous and controlled wastes, such as used chemicals;
- ☑ results are more likely to be achieved and maintained with a written plan and clear targets agreed by all areas of management.

The costs, savings and payback periods are provided as a rough guide only. They include estimates of up front costs such as capital, labour and installation, but do not include ongoing costs unless these are fundamental to the option itself (e.g. improved maintenance regimes).

The suitability and benefits of each option depend on the nature and size of the business and the scale of application. It should also check compliance with local environmental, safety and other requirements. The waste hierarchy provides a framework for managing waste: avoid; reduce; reuse; recycle; and dispose.

Some common waste reduction opportunities for small to medium automotive parts manufacturers are provided in the table following [26].

Table 2.1 Waste reduction opportunities for small to medium automotive parts manufacturers

OPTION	COST	SAVING	PAYBACK PERIOD	WASTE HIERARCHY
Manage stock and ordering to minimise packaging wastes.	nil	Packaging use /	Immediate	Avoidance
Separate waste streams to allow for collection of hazardous and recyclable liquid and solid wastes. Place signs on bins or walls to show what should be placed in each container.	nil	Waste to landfill	Immediate	Reuse/ Recycling
Collect sand used in foundries for recycling, and compost green sand in approved facilities. Bag house dusts may also be suitable for composting if dusts are controlled and have limited metal content.	$$	Waste to landfill	<1 year (Bag house dust 1-3 years)	Recycling
Reduce the cutting fluid content of metal swarf (eg centrifuge, magnetic separation or a gravity drainage system) to make it easier and safer to store and recycle through metal merchants. Swarf (especially from softer metals) can also be compressed into bricks using a bale press.	$$	Hazardous waste treatment and disposal	13 years (Bale press 5-10 years)	Recycling/ Compliance
Waste oil from cleaning and degreasing can be separated and filtered for recovery, or recycling. This can enable the reuse of the degreasing solution, or at least extend its life.	$$$$$$$	Chemical use and hazardous waste disposal	2-10 years	Reuse/ Recycling
Improve swarf drainage at cutting machines by increasing drainage times and by placing a screen above the bottom of the swarf collection bin.	$	Hazardous waste disposal	0-1 year	Avoidance
Minimise cleaning and degreasing requirements and extend tank life by keeping parts clean upstream and continuous oil extraction using an oil recovery system.	$$	Waste water treatment	2-4 years	Avoidance
Minimise plating and finish treatment rinses by reducing rinse flows and reusing second and third rinse water in earlier rinse cycles. Conductivity meters can be used to gauge contamination levels.	$$	Waste water treatment	1-2 years	Avoidance/ Recycling
Collect moulding and extrusion wastes for internal and external recycling.	$	Purchase of raw materials / waste	<1 year	Recycling
Recycle trim wastes and off-cuts from calendering and laminating.	$	Purchase of raw materials / waste	<1 year	Recycling
Recover (and treat if necessary) cooling and other waste water for reuse on-site instead of discharging to sewer.	$$	Water use and waste water treatment	2-5 years	Recycling/ Compliance
Fix leaks and review spill and chemical handling procedures. Use drip pans and vacuum systems to collect waste oil and other liquids that can be recycled (often free of charge) rather	$-$$	Hazardous waste treatment and disposal	0-3 years	Recycling
Improve spray painting efficiency by: ■ using paint monitoring software to calculate the exact amount of paint required (potential for 20% savings in paint use) ■ maintaining painting equipment (e.g. spray nozzles) ■ using high volume/low pressure spray guns.	$ - $$	Paint/solvent use and hazardous waste treatmentand disposal	<1 year each	Avoidance

$ up to $1,000	$$ $1,000 - $10,000	$$$ $10,000 - $50,000	$$$$ $50,000+

PROCESS CHANGE	MAINTENANCE	EQUIPMENT / PLANT UPGRADE

2.4.2 MAIN STRATEGIES FOR REDUCING AUTOMOTIVE WASTES AND MANAGING THE WASTES

IN-HOUSE PROGRAMS FOR WASTE REDUCTION

Most automobile companies understand that waste management requires a joint effort. They've come up with an in-house initiative aimed at raising waste management awareness.

This has seen the formation of alliances with third-party companies. They help automakers in waste management processes.

The programs also act as an incentive to the automobile employees, encouraging them to devise better ways of managing waste.

Main strategies for reducing automotive wastes and managing the wastes are [27]:

USE MORE ENVIRONMENTALLY FRIENDLY MATERIALS:

Use citrus-based solvents or recirculating spray wash cabinets for metal parts cleaning (instead of toxic chlorinated solvents).

Recycle used oils and solvents as much as possible.

KEEP A TIDY WORKSPACE: Spills happen, no matter how careful one is. Keep a tidy workspace, clean up any spills immediately, and consider using combustible absorbents to clean up spilled oil. The EPA recommends specific clean-up practices for handling used oil. Although not required, extraction devices such as centrifuges and compactors may be used to recover used oil from recyclable sorbent materials.

PREPARE MATERIALS FOR PICK UP: All waste materials should be kept in airtight, clearly labeled containers, prepared to be picked up by waste management responsible.

ESTABLISHING A REGULAR COLLECTION SCHEDULE AND DESIGNATED LOCATIONS: By having a regular collection time and designated locations, hazardous waste will not remain beyond the deadlines established by national regulations. Always contract with experienced hazardous waste disposal experts to comply with national regulations.

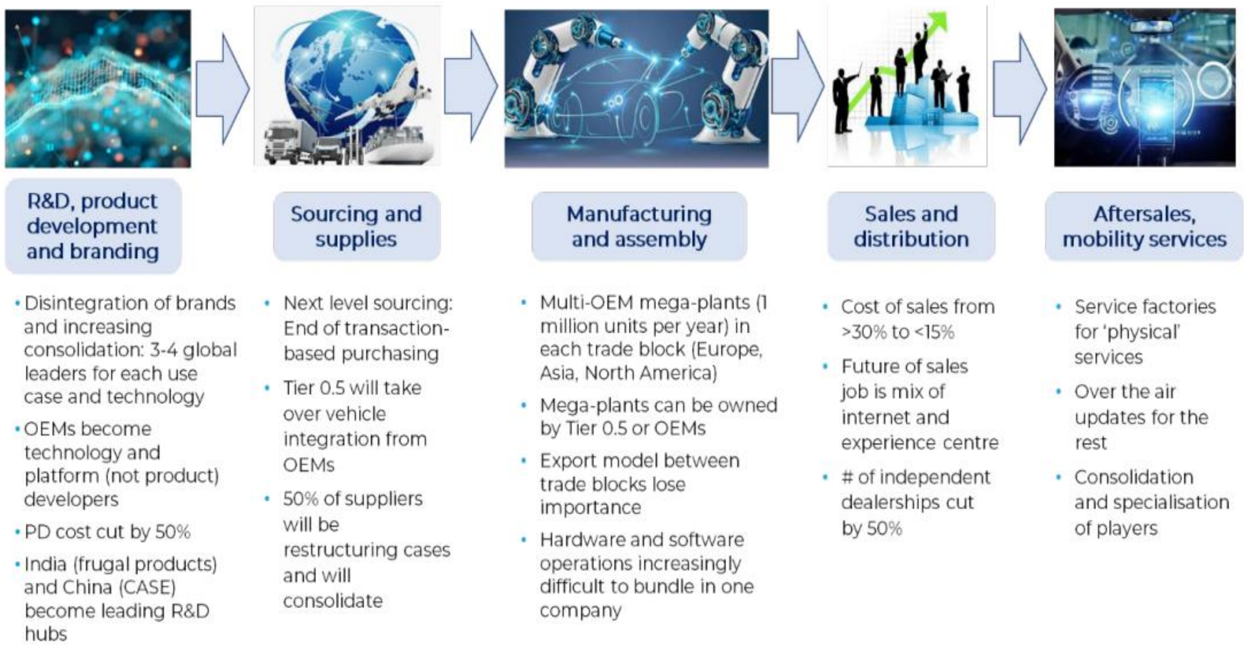
3 SUSTAINABILITY ACROSS THE AUTOMOTIVE VALUE-CHAIN

3.1 AUTOMOTIVE VALUE-CHAIN IN CIRCULAR ECONOMY

Developed by Michael Porter and used throughout the world for nearly 30 years, the **VALUE CHAIN** is a powerful tool for disaggregating a company into its strategically relevant activities in order to focus on the sources of competitive advantage, that is, the specific activities that result in higher prices or lower costs.

A company’s value chain is typically part of a larger value system that includes companies either upstream (suppliers) or downstream (distribution channels), or both. This perspective about how value is created forces managers to consider and see each activity not just as a cost, but as a step that has to add some increment of value to the finished product or service.

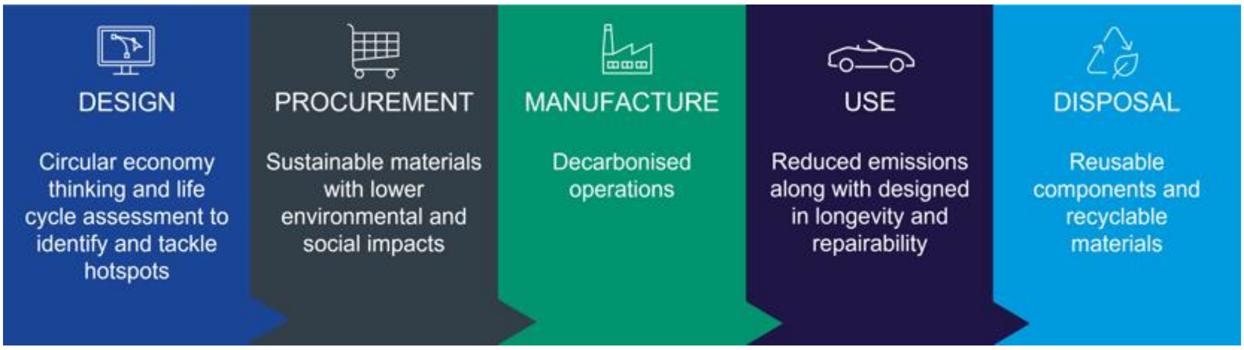
Current trends such as the electrification of vehicles and carbon neutral manufacturing demonstrate the growing importance of sustainability in the automotive industry. These trends are not just driven by the introduction of stricter emissions regulations, but also by increased awareness of environmental and sustainability issues within society and a growing demand from consumers for vehicles that have been manufactured in a more sustainable way as well as having a lower environmental impact during use and end of life.



3-1. Figure_ Changes in the automotive industry affect the whole value chain
[Source: Ecorys 2021 http://www.europarl.europa.eu/supporting-analyses]

As natural resources become more and more scarce, sustainable value chains are becoming increasingly important for the automotive industry. A circular economy is based on the principle of keeping resources in the value chain for as long as possible through approaches such as repair, reuse and recycling. This encompasses anything from tyres to the vehicle body shell, with the aim of extending the life of cars and their components.

Sustainability must be incorporated at every stage throughout the value chain.



3-2. Figure_ Sustainability throughout the value chain [https://www.ricardo.com/en/news-and-insights/insights/accelerating-sustainability-across-the-automotive-value-chain]

A circular economy model can be also supported by new business models such as sharing, leasing, repairing, refurbishing, and recycling materials and products, extending the lifetime and retaining value. Transparency along the supply chain is the only way to trace the origin of parts and ensure sustainability along the value chain. Consequently, automotive manufacturers and suppliers are considering how to implement innovative solutions to facilitate the tracking of raw materials.

3-3. Figure_ Typical Automotive Supply Chain

[https://doi.org/10.1016/j.cie.2021.107334]

The automotive industry is a major industrial and economic global force but it's also responsible for 7.3 billion metric tons of carbon dioxide emissions annually, with its detrimental impact on the environment. The industry is responding at last, with sustainability finally a key strategic priority and many automotive manufacturers adopting electric vehicles in efforts to achieve carbon neutrality. However, efforts are still needed if strategies are going to achieve their critical environmental targets [28].

One problem is that execution is often not holistic and therefore can be fragmented and less effective. If we are to achieve planet-saving sustainability, the whole industry needs to come together to review and adapt the entire automotive value chain: from material development and engineering all the way to manufacturing and operations.

Supporting a circular economy can help the automotive industry reduce the lifecycle carbon emissions per passenger km by up to 75% by 2030.

It requires **designing out waste from the value chain** by reducing or fully eliminating the use of fossil fuels and toxic chemicals and instead using sustainable resources such as:

- Renewable energy
- Biodegradable materials
- Reusable and recyclable materials.

While circular systems are already being deployed by 52% of organizations to enhance reuse, sharing, repair, remanufacturing, recycling and end-of-life practices with positive results, these initiatives need to be better applied collaboratively across the entire value chain and given equal importance at every stage.

Domains where the sustainable practices could be implemented:

R&D AND ENGINEERING

- Greener designs / product development, such as lighter, zero emission or electric vehicles
- Optimized use of natural, recyclable resources. Henkel, for example, uses renewable thermostats in paint shop sealants and coatings
- Optimizing use of biodegradable components, such as bioplastics

SUPPLY CHAIN

- Environmentally responsible sourcing of metals, materials and products
- Implementing mobility and digital sustainability services
- Lowering emissions
- Reducing transportation: moving from road to rail

MANUFACTURING AND OPERATIONS

- Maintenance, quality and production processes to reduce waste and improve recyclability and reuse of materials
- Renewable energy procurement
- Using recyclable packaging
- Implementing waste recycling, easy returns and responsible end of life disposal

- Collaborative eco production methods. For example, Henkel have created a number of low cure structural adhesives that reduce the manufacturing carbon impact. However, to be successful, the entire production chain needs to support lower temperature processes.

MARKETING & SALES

- Take back vehicle schemes for refurbishment and reuse.

3.2 DESIGNING VEHICLES USING RENEWABLE RESOURCES

The automobile industry is doing a remarkable job in developing renewable resources. These resources aim to lower the amount of petroleum used for production. As a result, there's a reduced carbon footprint.

For now, renewable materials are suitable for designing passenger seats of vehicles. However, there are ongoing experiments aimed at in-cooperating renewable resources vehicle's design.

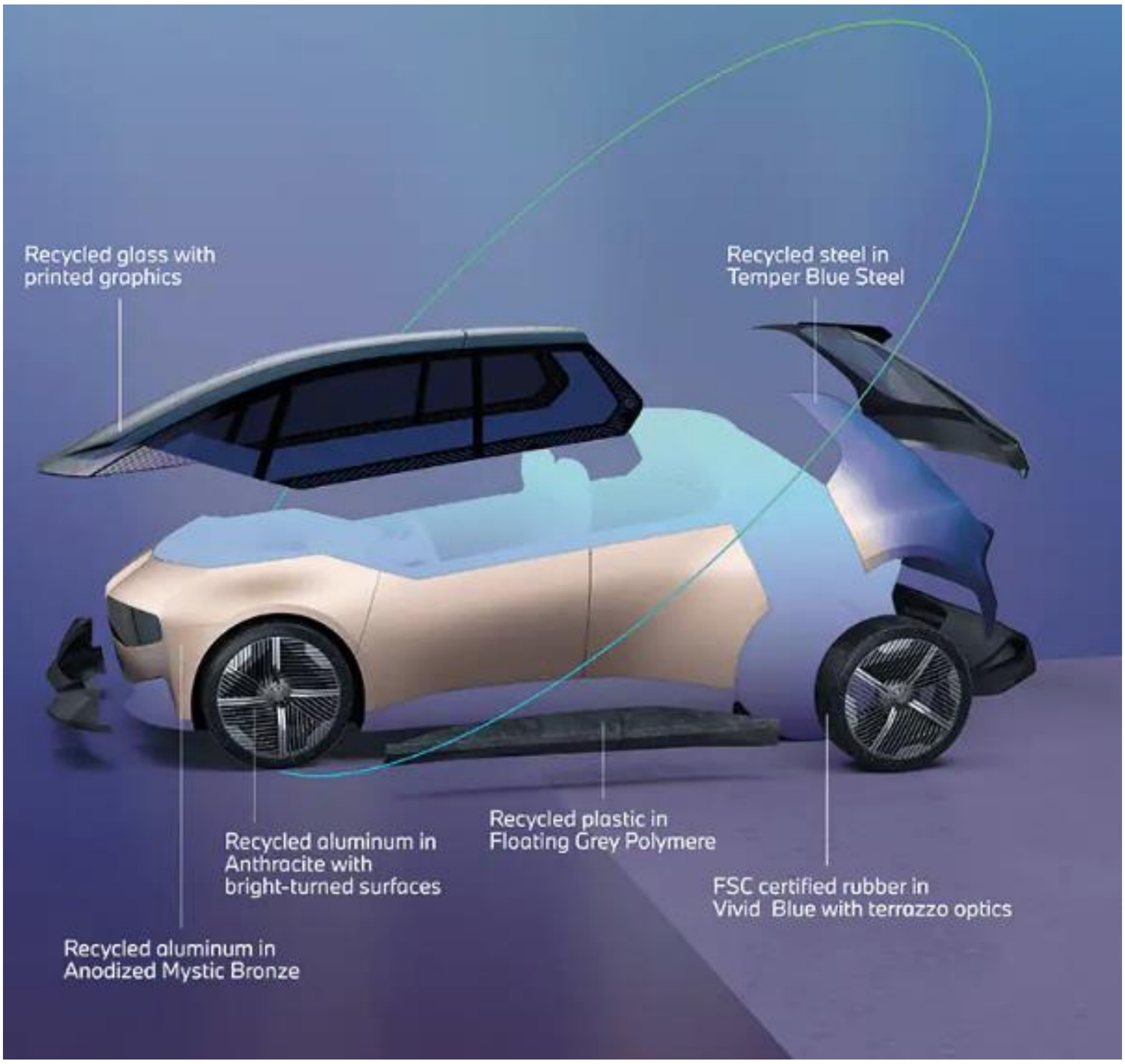
Renewable, plant-based materials are also part of **FORD** sustainability strategy. Ford is using nine plant-based materials in current and past vehicle production. These robust materials have multiple benefits including enabling lighter weight parts that improve fuel economy, sequestering carbon and reducing global warming impacts, and also require less energy to manufacture. Ford industry-first sustainable materials include soy foam, wheat straw, rice hulls, tree-based cellulose, and coffee chaff.

Soy seat cushions, backs and headrests were one of many Ford firsts. They have been used in every Ford North American built vehicle for more than a decade, over 18.5 million vehicles. Bio-based foams have reduced greenhouse gas emissions by over 228 million pounds, and use of soy foam, launched on Mustang and now on all American vehicles, has helped save 5 million pounds of petroleum annually since 2008.

Ford Advanced Polymer Technologies team continues to pioneer the development of new sustainable plastic materials including using waste from olive production to reinforce plastics, captured carbon dioxide in plastic formulation and polymer resins made from renewable feed stocks. For example, it is tested whether the tree-based cellulose composites, that were incorporated into Lincoln Continental consoles, can be used in other applications. Ford experts are also deriving value from waste material, using recycled ocean plastics in the Bronco Sport.

Another example is **THE BMW I VISION CIRCULAR** – a fully-electric four-seater with a consistent focus on sustainability and luxury –emblematic of the ambition of the BMW Group to become the most sustainable manufacturer for individual premium mobility.

The BMW i Vision Circular is a vision vehicle from the automobile manufacturer BMW and gives a foretaste of the year 2040. The focus of this concept car is on sustainability and luxury. It consistently followed circular economy principles in its design with the intent to reduce CO_2 emissions.



3-4. Figure_ BMW i Vision Circular
[https://www.bmw.com/en/events/iaa2021/bmw-i-vision-circular-domagoj-dukec-first-look.html]

USE OF RENEWABLE RAW MATERIALS - ŠKODA, in collaboration with the Technical University of Liberec and the supplier, has developed a sustainable, ecological material made from sugar beet pulp which can be used in dyed form in the interior of vehicles to create certain design accents. In addition, ŠKODA is working on another material based on the miscanthus reed which will also be used in the interior of models in the future [[29]]. The use of rice husks, hemp, cork and coconut fibres is also being researched. ŠKODA is deploying used high-voltage batteries from electric vehicles in stationary energy storage systems before they are recycled. This second life cycle effectively reduces the batteries' CO2 footprint [29].

The VW Group is investigating the use of other ecologically sourced materials, such as materials based on cellulose.

TOYOTA has successfully used bio-renewable materials. The car models use the soybean-based polyurethane foam on seats.

3.3 RECYCLING AND REUSING

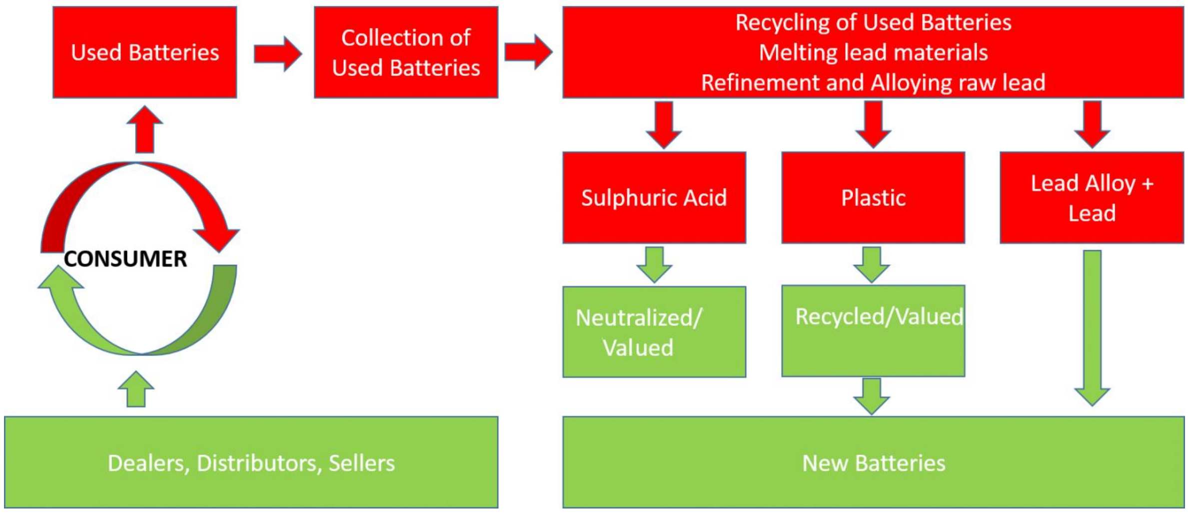
Recycling and reusing materials from vehicles play a huge role in reducing waste. These efforts have a ripple effect on other related industries. For instance, recycled steel contributes to energy savings in the steel manufacturing industry. To maintain the integrity of the material, the companies have adopted closed-loop recycling. This means adopting self-sufficient recycling processes.

However, only 80% of a vehicle is recyclable. The remaining unrecyclable parts end up disposed of in landfills. Reusing and selling these unrecyclable materials is a more viable option.

Car manufacturing companies are also using parts that are easy to dismantle. This ensures the separating of parts is easy and safe, without damaging the parts.

Example: **ROMBAT SA** is the largest producer of car batteries in Romania [[30]]. Rombat is present both in European countries, such as France, Italy, Germany, Serbia, North Macedonia, Bulgaria, the Republic of Moldova, Greece, Hungary, Russia, Ukraine, Spain, as well as in Asia, Africa and North America [[31]].

Since 2005, the company has been collecting vehicle batteries to extract the lead they contain, recycle them and manufacture new batteries. The batteries are processed at the 3.7 ha Rebat facility in Copșa Mică [[32]]. Over 83% of the battery weight is reused in new processes (3-5. Figure). Rombat encourages owners of used automotive and industrial batteries in ebonite or polypropylene boxes to contact them for collection and cooperation. The company recycles part of the 30 000 tons of batteries that are placed on the market in Romania each year. They distribute batteries in more than 3000 stores across the country, as well as in France and Germany. The company aims to reduce its environmental impact by improving its batteries and enhancing battery recycling services to avoid using up more of Romania's natural resources.



3-5. Figure_ROMBAT Recycling Process of the batteries

[Source: https://www.rombat.ro/en/company/rebat/]

ROMBAT applies the operating principles of the circular economy, annually managing to recycle 24,000 tons of used batteries, 98 percent of this amount being reintroduced into the production cycle [[33]]. The company extracts around 12 000 tons of lead from old batteries each year, making it one of the leading car battery recyclers in Romania. Over 83% of a battery's weight is reused when it is recycled; lead, lead alloy and plastic are reused in new batteries.

3.4 REPAIR VS REMANUFACTURING

Repair is the process of bringing damaged components back to a functional condition by repairing the broken or damaged component of the product.

Remanufacturing is the process of bringing a product back to the same condition as a new product. This means that all components are checked and remanufactured, and any component that cannot be remanufactured is replaced with a new one.

Remanufacturing, also called ‘reman’, is a branch in the aftermarket industry.

A **REMANUFACTURED PRODUCT** is defined as: "A remanufactured part fulfils a similar function as the original part. It is restored from an existing part (core) using standardised industrial processes in line with specific technical specifications. A remanufactured part is given the same warranty as a new part, and it clearly identifies the part as a remanufactured part and states the remanufacturer." (This is the common definition from APRA -Automotive Parts Remanufacturers Association in USA, Europe and Asia, CLEPA- European Association of Automotive Suppliers, FIRM International Federation of Engine Remanufacturers and Rebuilders, Europe, supported by MERA Motor and Equipment Remanufacturers Association, USA, and RIC Remanufacturing Industries Council, USA).

REMANUFACTURING AUTOMOTIVE PARTS means renovating used parts or components to OE-matching condition.

The remanufacturing industry has existed for approximately 70 years. Prior to the industry, defect units were simply regarded as scrap.

Aside from the considerable economic and environmental benefits of remanufacturing, is possible to detect the most frequent causes for defects affecting the units received for remanufacturing. This allows to take the necessary precautions and reproduce products that match OE-standards.

Remanufacturing is a significant contributor to a circular economy, where as much material as possible is given new life, and as little as possible goes to waste. To remanufacture automotive parts, used products, namely cores, should be retrieved. The collection of cores is a complex activity.

EXAMPLE: BORG Automotive Reman sells the remanufactured units with a deposit, which is returned to the customers if they send back the unit they are replacing. The core that BORG receives in exchange for a remanufactured unit is sent to the central warehouse in Poland, the largest core warehouse in Europe, with more than one million units ready for remanufacturing. At production sites, auto parts undergo the remanufacturing process. This process involves complete disassembly, thorough cleaning, extensive inspection of all parts, reconditioning and replacement, reassembly, and final testing [34].

ENVIRONMENTAL BENEFITS OF REMANUFACTURING

- is a significant contributor to a circular economy, where as much material as possible is given new life, and as little as possible goes to waste.
- extends the product's life span by bringing a defective product to the same standard as it was when it was first manufactured. Letting it undergo a process that aims to recover most of the material - without compromising the quality. Consequently, the environmental impact is also minimised.
- saves, on average, 96% of the raw materials used in manufacturing the original automotive part (starters and turbochargers). Furthermore, the CO2es are reduced by approximately 40% and the energy by approximately 38%. The transport capacity is more or less the same, with a reduction of 0.12% [35].

3.5 GROUPE RENAULT - CLOSED-LOOP RECYCLING SOLUTIONS, CAR-TO-CAR

Every year in Europe more than 11 million vehicles, which include around 85% recyclable materials, reach the end of their life cycle. However, this resource is under-exploited: new vehicles contain only 20% to 30% recycled materials, which come from all industries. Currently, recyclable materials from end-of-life vehicles are mainly recovered for other industrial applications (metallurgy, construction, etc.).

Renault is a pioneer of the circular economy in the automotive industry. The aim of their circular activities is to extend the life of vehicles and components, and keep materials in use, thereby reducing the use of virgin materials [36]. It has achieved this in different parts of the manufacturing process and across different brands. For example, by: remanufacturing vehicle components such as gear boxes and turbo compressors; increasing recycled plastic content; creating a second life for electric batteries.

In 2020, Groupe Renault increased their ambition level and established **'RE:FACTORY',** Europe's first dedicated circular economy factory for vehicles and mobility [37]. Renault transformation plan is deployed gradually between 2021 and 2024 and the site will be organised around 4 activity centres, each with its own field of expertise: **RE-TROFIT, RE-ENERGY, RE-CYCLE AND RE-START**, in order to support the entire life of the vehicle by acting on the main components of the circular economy (supply, eco-design, economy of functionality, maintenance, reuse, remanufacturing and recycling) [38].

The objective of The Future Is NEUTRAL is to maintain the value of parts and materials for as long as possible and to enable the automotive industry to use in the future in the manufacture of new vehicles a much higher percentage of recycled materials from end-of-life cars.

The new company has a network of subsidiaries and partners that ensure, throughout the entire life cycle of a vehicle, the collection of parts, materials and batteries from various sources, from factory scrap to car workshops. Thanks to this ecosystem, The Future Is NEUTRAL develops circular economy loops at every stage of a vehicle's life, from production, to use, to end-of-life.

Specifically, The Future Is NEUTRAL benefits from the expertise of the Gaia subsidiary whose activities in the field of battery repair, collection and reuse of parts and recycling of materials recovered at the end of a car's life cycle are carried out in the factory in the French city of Flins.

INDRA, a competitive end-of-life vehicles treatment branch, recovers up to 95% of car mass.

The Future Is NEUTRAL will also offer advisory and training services dedicated to the circular economy to the automotive sector, with the support of the Campus of the Circular Mobility Industry (ICM) based in the city of Flins, within the company University "ReKnow University" of the Renault Group.

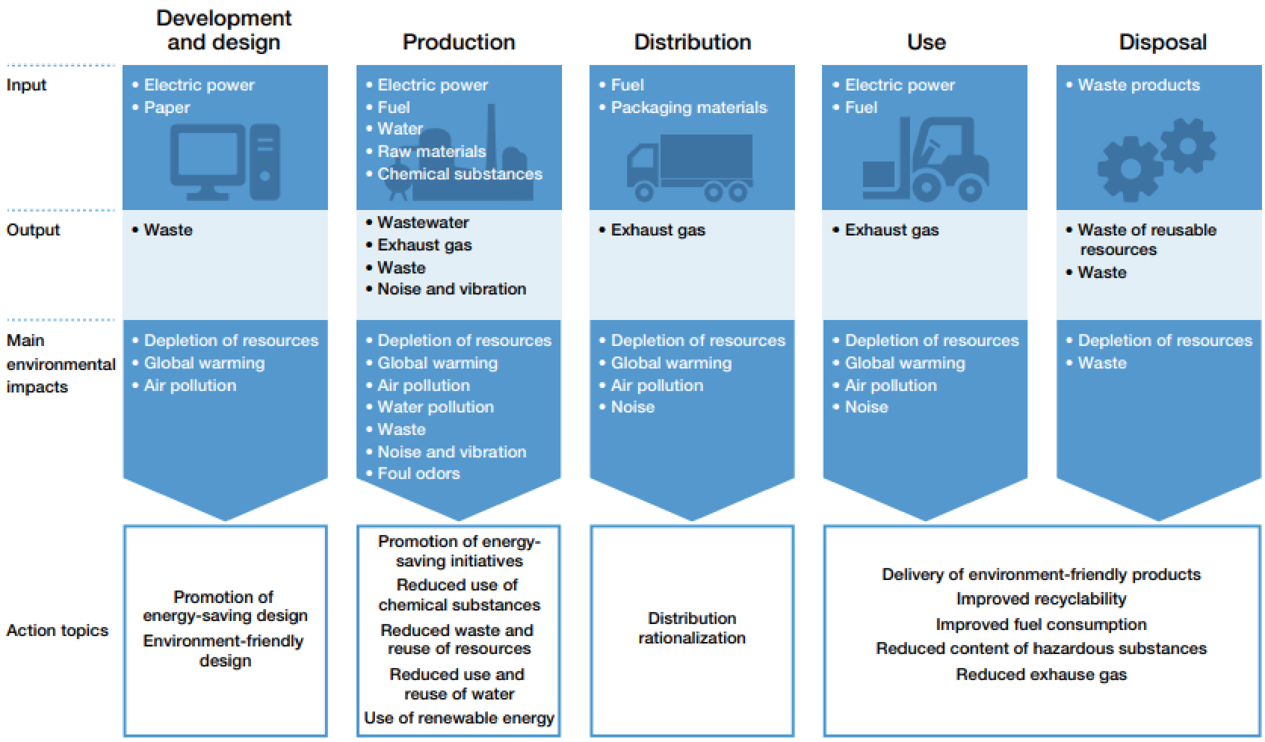
3.6 ENVIRONMENTAL IMPACT OF BUSINESS ACTIVITIES

Toyota have been striving to grasp the overall picture of the use of natural resources and energy, and the consequential environmental impact over the entire life cycle of the product from the planning, development and design of a new product to its disposal, with the aim of promoting efficient activities and reducing environmental impact.

THE INPUT includes sources of energy such as power, water, paper used in offices, raw materials used for manufacturing the product, various kinds of chemical substances used in the production process, and fuel for transport vehicles used in the distribution stage. The effect of their consumption is the depletion of natural resources.

THE OUTPUT includes wastewater, exhaust gas and other wastes generated in the manufacturing stages, and carbon dioxide produced by the consumption of fuel and energy, which have various environmental impacts.

TO REDUCE these environmental impacts, Toyota have been establishing daily controls, setting goals and promoting environmental activities.



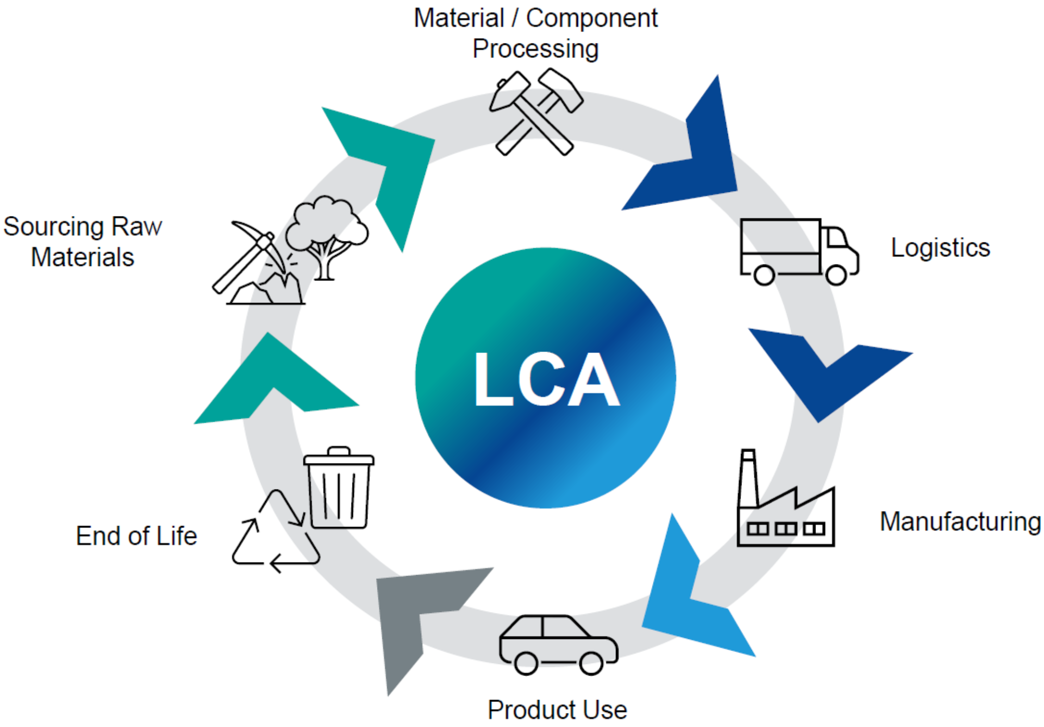
3-6. Figure_Environmental impact of business activities – TOYOTA

[Environmental Management | Toyota Industries Corporation (toyota-industries.com)]

3.7 Life Cycle Assessment

LCA (Life Cycle Assessment) is a method of assessing the environmental impact of a product or service throughout its life cycle (resource extraction - raw material production - product production - distribution and consumption - disposal and recycling).

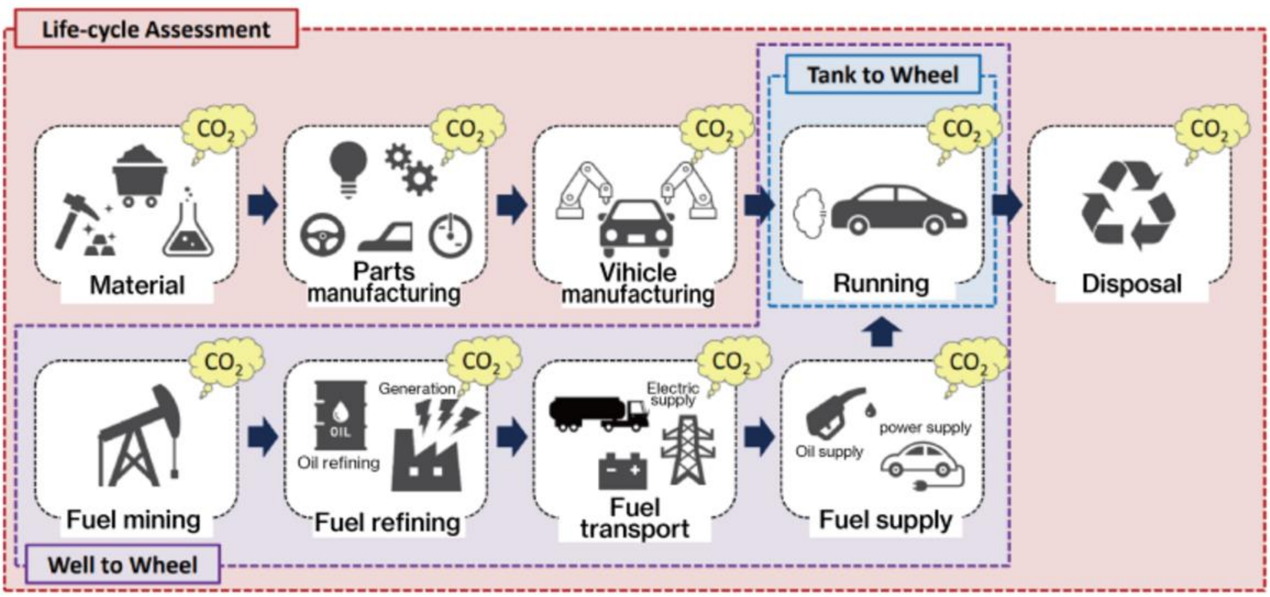
LCA is a method for evaluating the environmental impact of products and services throughout their life cycle (resource extraction - raw material production - product production - distribution and consumption - disposal and recycling). LCA is specified in the international standards ISO 14040 and 14044.



3-7. Figure_Life Cycle Assessment

[https://www.horiba.com/esp/applications/energy-and-environment/energy-usage-optimization/lca/]

The 3-8. Figure is an overview of LCA for automobiles. Conventionally, the focus was only on CO2 emissions during driving. Nowadays, however, as required by LCA, it is the manufacturer's responsibility to reduce environmental impacts at all phases of the product life cycle, from fuel mining and materials procurement to manufacturing, use, disposal, and recycling.



3-8. Figure_ LCA for automobiles
[https://www.horiba.com/esp/applications/energy-and-environment/energy-usage-optimization/lca/]

A full life cycle assessment (LCA) of a vehicle's emissions is an essential step towards sustainable use of the world's resources. An LCA covers production of the raw materials, use of the product, and its end of life including recycling and reuse. It enables manufacturers and material suppliers to accurately evaluate the potential environmental impact of their products or materials over their life cycle.

3-9. Figure_ The three phases of a complete life cycle assessment
[https://automotive.arcelormittal.com/sustainability/life_cycle_assessment]

Current regulations in the automotive sector only focus on the use phase of a vehicle's life. This pushes carmakers to reduce weight but ignores the production and end-of-life phases of a car's lifecycle.

While the use phase of an internal combustion vehicle's life cycle currently produces the most greenhouse gas emissions, this is not the case for emerging powertrains. Vehicles powered by solar-generated electricity or bio-fuels have very low levels of emissions during their useful life, making the production and end-of-life phases more important.

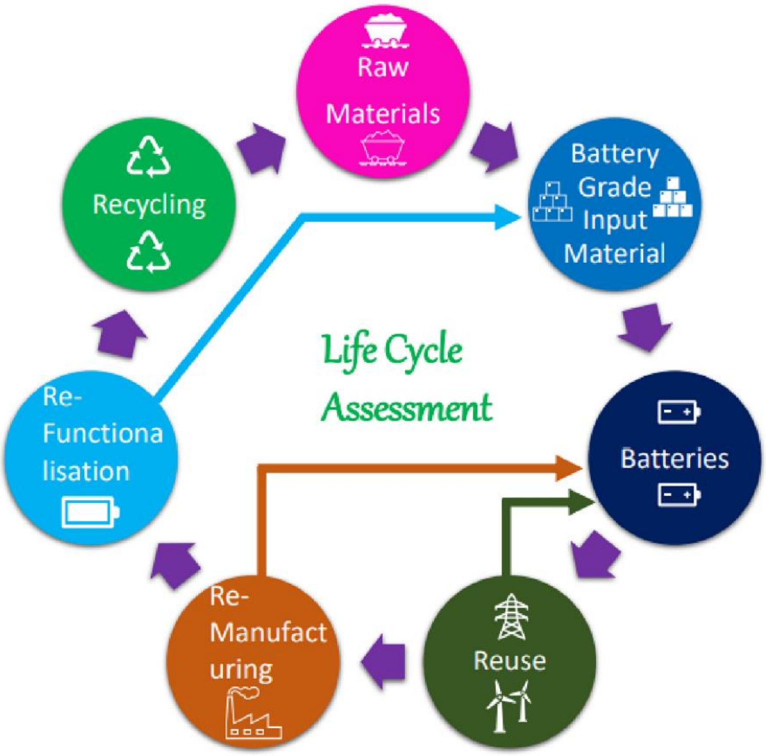
To address these concerns, the introduction of LCA emissions legislation which covers the vehicle's entire life is necessary.

Current regulations in most parts of the world only consider the use phase of the vehicle's life.

Adopting a life cycle assessment (LCA) approach to regulation ensures that emissions across all phases of a vehicle's life cycle, and the supply chain, are considered.

While existing legislation has driven down tailpipe emissions during the use phase, it has also shifted the environmental burden to the production and recycling phases of the vehicle's life. The unintended consequence is that overall transportation emissions might increase, even as tailpipe emissions are lowered. Emissions from the manufacture and disposal phases of a vehicle's life are an increasingly significant part of its life cycle emissions. This is particularly noticeable in vehicles made from synthetic materials.

Adopting an LCA approach would encourage emission savings across life cycle phases and the supply chain. Ultimately it would ensure that overall emissions from transportation are lowered. The LCA approach would also give carmakers a wider range of material options and benefit their competitiveness.



3-10. Figure_ LCA of Li-ion battery from its “cradle” to “grave”
[https://doi.org/10.1002/wene.481]

Through the LCA analysis, it is possible to know the environmental feasibility of LIB recycling, whether the recycling increases the environmental burdens or decreases the environmental impacts.

3.8 ELV TOWARDS CIRCULARITY AND SUSTAINABILITY

3.8.1 End-of-Life Vehicles

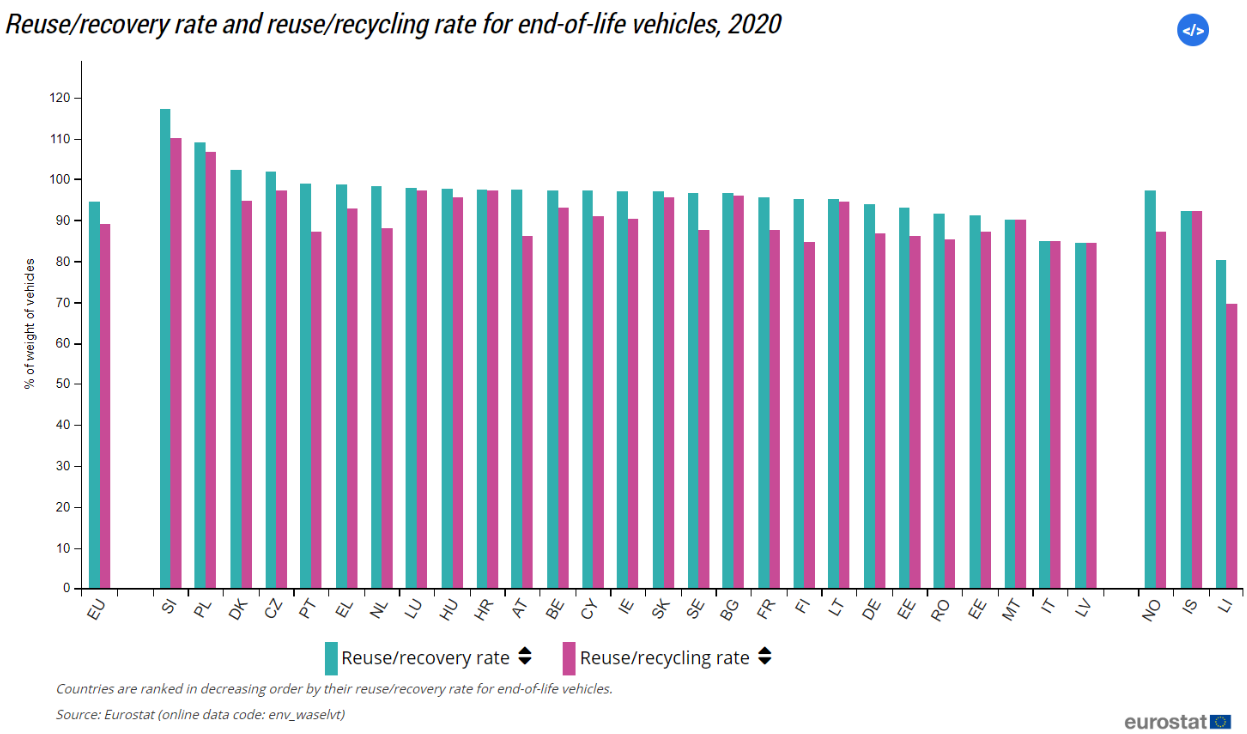
END-OF-LIFE VEHICLES are vehicles that have ended their useful service and are processed as waste, in practice dismantled, shredded or otherwise disposed.

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.

The data cover end-of-life passenger cars and light goods vehicles such as vans and pick-ups.

5.4 million passenger cars, vans and other light goods vehicles were scrapped in the EU in 2020. The total weight of passenger cars, vans and other light goods vehicles scrapped in the EU in 2020 was 6.2 million tonnes; 94.6 % of the parts and materials were reused and recovered, while 89.1 % were reused and recycled [39].



3-11. Figure_Reuse/recovery rate and reuse/recycling rate for end-of-life vehicles, 2020

[Source: EUROSTAT, 2020]

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.

End-of-life vehicles have no negative value and need to be scrapped as they're considered waste [40].

There are two types of ELVs – natural and premature [41]. Natural ELVs are vehicles which lose technical or economic value because they're used and old, while premature ELVs lose value due to accidents and are written off.

These ELVs contain both useful and hazardous components. Each year, 8 to 9 million tonnes of waste are produced by end-of-life vehicles (ELVs) in the EU, of which 25 per cent is hazardous. Of this, 6.9 million tonnes of vehicle waste was scrapped in the EU in 2019.

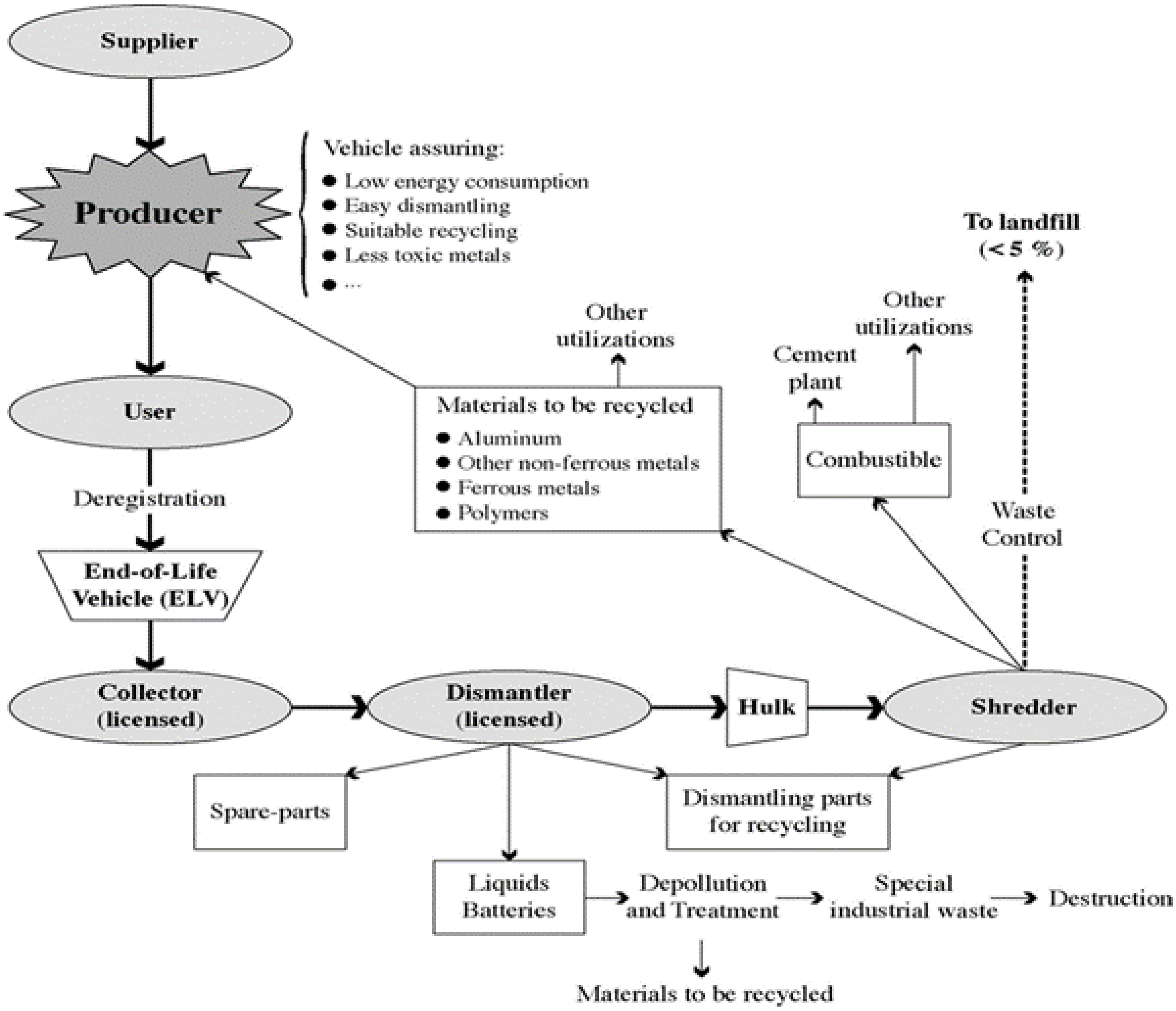
5.4 million passenger cars, vans and other light goods vehicles were scrapped in the EU in 2020.

The European End of Life Vehicles Directive makes producers and importers responsible for limiting the environmental and safety impact of automobile waste.

As prescribed by the ELV Directive, all stakeholders in the vehicle life cycle have a role to play and ELVs must go through the following steps in the ELVs disposal route [3, 40, 42] (as shown in 3-12. Figure):

- Owners must bring the end-of-life vehicle to their new or used car dealer. The dealers send the ELVs to collectors or dismantlers.
- Car owners have to get a certificate of destruction from the car dealer or authorised collecting and treatment facilities to deregister the vehicle, depending on the country.
- Authorised dismantlers and collectors dismantle the car to remove reusable parts for sale, such as engines, gearboxes, body parts, airbags, etc. Dismantlers also depollute ELVs by removing batteries and draining air conditioner fluids and oils in a safe environment. They also have permission to destroy special waste. Thorough separation by dismantlers can significantly reduce waste in subsequent stages.
- Shredders further dismantle car parts but also shred the body. Metal components get separated from the nonmetals and are sent for recycling, back to vehicle producers to make the same components, or sent to other users. Automobile shredder residue (ASR) is composed of non-metal items (fabric, paper, wood, plastic, rubber, etc.) and iron.
- Energy recovery is the next step. Combustible parts of the car in ASR are used instead of other fuels in industrial processes like cement production.
- Landfilling of the remaining ASR occurs after strict control. The ELV Directive aims to reduce landfilling to less than 5 per cent of the materials in ELV.

Despite the ELV Directive, about one-third of ELVs in the EU is not deregistered. These are illegally exported and scrapped or abandoned.



3-12. Figure_ Steps in ELV Recycling according to the EVL directive [42]

END-OF-LIFE TIRES (ELTS) must also be treated, because, under Directive 2000/53/EC, the reuse, recycling, and recovery of any part of the vehicle must also have no negative safety or environmental impact.

Moreover, the Commission Decision 2003/138/EC of 27 February 2003, in keeping with the ELV Directive 2000/53/EC, has established component and material coding standards for rubber (elastomers) and plastics and requires separate recovery of these materials after dismantling. Since tires have both rubber and plastics, they form a separate waste stream.

These ELTs have become a global waste problem since most methods to recycle them also have a negative environmental and safety impact. Moreover, though ELTs are classified as non-hazardous waste, they do contain heavy metals, so they have to be handled with care.

To comply with Directive 2000/53/EC, manufacturers must produce tires from which they can recycle at least 85 per cent and recover 95 per cent of materials. These requirements are spurring a movement towards circularity to recover and recycle material from waste tires.

Newer technologies like pyrolysis have caught the attention of the tire industry as it's the most efficient and sustainable recycling option for tires.

For example, the new improved Contec pyrolysis process can recover 85 per cent of materials in the form of products such as Carbon Black, oil, gas, and steel [43].

By using 20 per cent of the pyrolytic from recovered Carbon Black as reinforcing filler, tire rubbers can ensure compliance with the ELV Directive clause, which requires manufacturers to incorporate recycled material in their production.

HOW CAR MANUFACTURERS ARE AFFECTED

Besides recovering and recycling material, vehicle manufacturers and importers have several other responsibilities under the ELV Directive. They're the pivot between upstream (raw materials) and downstream for vehicles:

- **Producers must design vehicles** that are easy to dismantle, reuse, and recycle, and are hazardous substance-free, as it can have a significant impact on the entire life cycle of vehicles. The use of heavy metals such as cadmium, lead, mercury, and hexavalent chromium is restricted in-vehicle components. And the production process must also use less energy.
- **Manufacturers and importers** must be aware of the recycling efficiencies, rate, and capacity of downstream or waste disposal centres.
- **Importers and manufacturers** must pass on information for dismantling, recycling, and treating components in each model of car and light vehicles below 3.5 tonnes.
- **Importers, manufacturers, and distributors** must set up or participate in integrated systems for the free take-back of ELVs within their territory. In most countries, suppliers of individual brands have their own collection systems. In countries like Denmark, a network of dealers collect all vehicles in their area. Spain has a variety of dealers and municipal and authorised treatment centres that collect ELVs.
- **Producers and importers** are also responsible for covering the costs of the collection and treatment of ELV waste.
- **Producers and importers of vehicles** are responsible for meeting the recycling and recovery targets set by the ELV Directive.

Though producers and suppliers have a major role to play, coordinated action by all players is necessary for any country to achieve the ELV Directive goals of ushering in a green and sustainable change in the vehicle industry.

3.8.2 ENVIRONMENTALLY FRIENDLY ELV RECYCLING SYSTEM

How end-of-life vehicles (ELV) are handled is a major concern in today's society, especially when you consider that 1.23 billion cars will become waste all over the world. Thus, there needs to be some kind of appropriate processing and recycling for cars of all kinds.

KAIHO INDUSTRY Japonia is a car recycling company that offers a solution that addresses waste treatment and management of ELV (end-of-life) vehicles. The company was presented by the United Nations Organization for Industrial Development as part of the Platform for the Promotion of Sustainable Technologies [[44]].

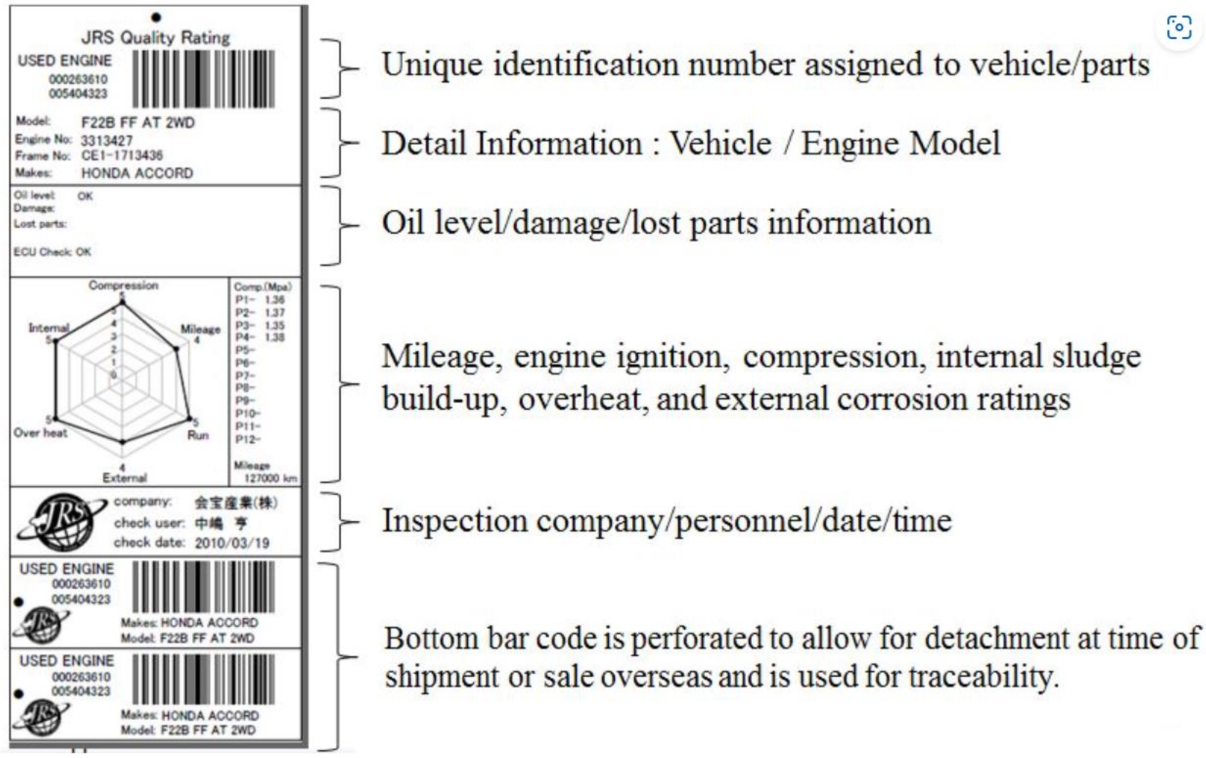
The company has developed an environmentally friendly car recycling system that contributes to the circular economy.

It is delivered in the form of a "package car recycling system", consisting of three components:

- ⇨ Installation of automobile recycling equipment and production system - an adaptable standardized recycling technology that allows the separation of scrap metal from used recyclable parts;
- ⇨ Installation of computerized business management system called KRA - the system enables quality control and inventory management, using a barcode system to identify the origin, history and specifications of individual parts recovered from vehicles;
- ⇨ Provision of training on automobile recycling technologies and management skills - The International Recycling Education Center (IREC) imparts both technologies and management skills to recycling workers.

The recycling solution contains a standard for evaluating the quality of used engines that reach the export market, called the Japan Reuse Standard (JRS).

This quality standard for used products complements the Japanese Industrial Standard for new products. A representation of this is provided in the figure below.



3-13. Figure_ Japan Reuse Standard (JRS)

[Auto Recycling: Eco-Friendly ELV Recycling System | United Nations Industrial Development Organization (unido.or.jp)]

The information provided on the quality standard sheet is the essential information to ensure transparency regarding the potential life and performance of the engine and related drive unit.

4 STRATEGIES AND BUSINESS MODELS THAT HELP REDUCE WASTE IN THE AUTOMOTIVE INDUSTRY

The circular economy paradigm focuses on reducing non-renewable materials and energy, promoting renewable raw materials and energy, and keeping products/materials in use throughout the life cycle of a system. As such, the life-cycle environmental burdens associated with the manufacture, use and disposal of vehicles could be reduced through circular economy strategies.

Automobile and component manufacturers are concerned with implementing the circular economy to increase product sustainability.

4.1 RESOLVE

There are different business models applied to circularity, ranging from proposals of different types of models to practices and tools of circular business models [[45]] [[46]] [[47]]. Among them is ReSOLVE [[48]], a business model easy to apply in different organizational contexts, which proposes a set of six fundamental actions (Regeneration, Joint use/shared use, Optimization, Loop, Virtualization, Exchange), on which companies can carry out, as key accelerators of the transition to a circular economy.

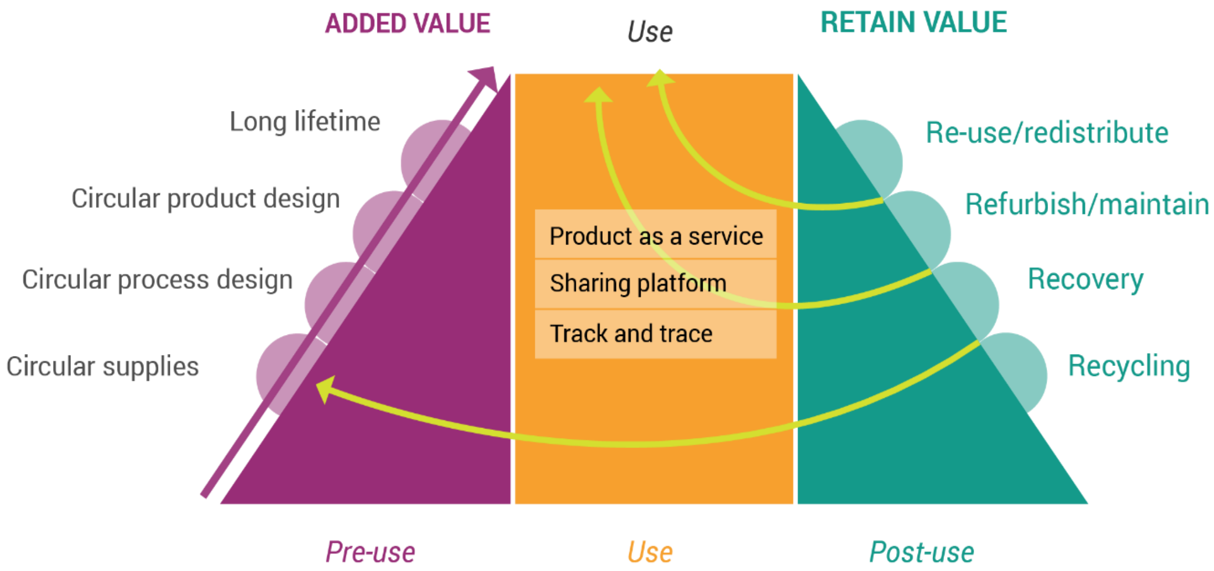
ReSOLVE enables companies to establish an overview of the possibilities and map the potential opportunities of the circular economy in all their sectors.

4.2 THE VALUE HILL MODEL OF THE CIRCULAR ECONOMY

To help businesses position themselves in a circular context and develop future strategies for doing business in a circular economy, Sustainable Finance Lab, Circle Economy, Nuovalente, TUDelft, and het Groene Brein got together to create the Value Hill [49].

The Value Hill proposes a categorisation based on the lifecycle phases of a product: pre-, in- and post- use. This allows businesses to position themselves on the Value Hill and understand possible circular strategies they can implement as well as identify missing partners in their circular network. The Value Hill provides an overview of the circular partners and collaborations essential to the success of a circular value network.

A circular economy combines different processes in the life cycle of a digital device. These processes are interdependent and create new loops within the wider life cycle of a product.



4-1. Figure_ The Value Hill
(Source: The Sustainable Finance Lab, 2016)

The Value Hill model of the circular economy provides an understanding of how to position these processes in terms of value (usefulness) in a circular context.

As shown in Figure above, value increases as the product is developed in the pre-use phase (left uphill slope). The flat top of the hill represents the in-use or use phase of a device when the product's value is at its maximum. After one cycle of use, the product's value decreases in the post-use phase (right downhill slope).

Circular choices in each of the processes of the three phases are interrelated. Choices in the uphill phase can contribute to and prolong the use phase, and facilitate a slow descent in the downhill phase.

Reuse, refurbishment and maintenance of a device, facilitated by circular product design, can return devices back to use, or the flat top of the hill.

Finally, the recovery of parts and materials is facilitated by good decisions in the circular design and manufacturing processes.

The circular economy tries to maintain devices as resources with the highest possible value for as long as possible. Inevitably, value can diminish, but regenerative processes can return them to a higher value through refurbishment, repair and maintenance to find and satisfy the needs of a new user, or to a lower value through recovery of components, recycling with recovery of any useful material, or minimising the impact of the unrecoverable fraction (e.g. separate, compact and treat toxic materials to prevent damage).

The Value Hill also provides a practical tool and language to position a business in a circular context and to identify gaps and opportunities to transition to a circular business strategy [[50]].

Table 4.1 Detailed Overview of Business Models per Value Hill category
[www.circle-economy.com/financing-circular-business]

Value Hill Category	Business Model	Description
Circular Design (Uphill)	Circular product design	Designing products with their end-of-life in mind by making them easy to maintain, repair, upgrade, refurbish or remanufacture
	Classic long life	Delivering longevity of a product with high levels of guarantees and services for a high price upfront.
	Encourage sufficiency	A high price per product can justify lower volumes
	Circular materials	Utilise input materials such as renewable energy, bio-based-, less resource intensive- or fully recyclable materials
Optimal Use (Tophill)	Life Extension	Sells consumables, spare parts and add-ons to support the longevity of products
	Repair & Maintenance Service	Repairs, maintains and possibly upgrades products that are still in use
	Product leasing (Product as a Service)	Delivers access to a product rather than the product itself so that the service provider retains ownership of the product. The primary revenue stream comes from payments for the use of the product and a single user uses the product at any given time.
	Product renting (Product as a Service)	Delivers access to a product rather than the product itself so that the service provider retains ownership of the product. The primary revenue stream comes from payments for the use of the product and different users use the product sequentially.
	Performance provider (Product as a Service)	Delivers product performance rather than the product itself through a combination of product and services, where no predetermined product is involved and the service provider retains ownership of the product. The primary revenue stream is

Value Hill Category	Business Model	Description
		payments for performance of the product, i.e. pay-per-service unit or another functional result.
	Sharing Platforms	Enables an increased utilization rate of products by enabling or offering shared use/access or ownership through which, different users use the product sequentially.
	Sell and buy-back	Provides a product and agrees on repurchasing the product after some time.
Value Recovery (Downhill)	Recaptured material supplier	Supplies recaptured materials and components to substitute the use of virgin or recycled material
	Refurbisher	Refurbishes used products if necessary and re-sells them
	Second hand seller	Provides used products
	Remanufacturer	Provides products from recaptured materials and components.
	Recycling facility	Transforms waste into raw materials. Additional revenue can be created through pioneering work in recycling technology.
Network Organisation (Cross-hill)	Recovery provider	Provides take back systems and collection services to recover useful resources out of disposed products or by-products
	Process design	Provides services around processes that increase the re-use potential and recyclability of industrial and other products, by-products and waste streams
	Value management	Provides services around managing information, materials, transparency, payments and governance in a circular value network. For example ICT solutions for smart contracts and payment systems, or consultancy on circular management systems
	Tracing facility	Services to facilitate the trading and the marketing of secondary raw materials

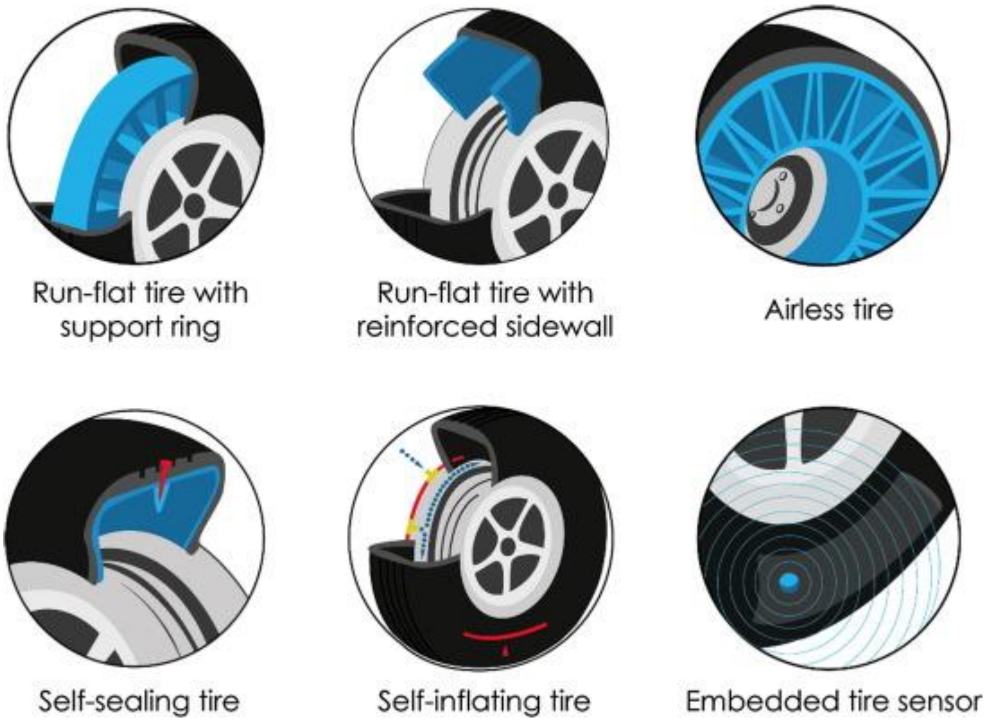
5 CASE STUDY - APPLYING CIRCULAR ECONOMY PRINCIPLES TO THE TIRE INDUSTRY

The concept of 3R (Reduce, Reuse, Recycle) tried to develop responsible consumption habits. However, the growth of ecological thinking has given rise to four new Rs in addition to these basic 3Rs; the 7 R's today (Reduce, Reuse, Recycle, Redesign, Renew, Repair and Recover) which refer to the actions needed to facilitate and accelerate the transition to a circular economy in the tire industry.

Next, a model will be detailed that aims to extend the life of resources by using them rationally and efficiently to generate value repeatedly, reducing costs and waste. The tire journey from a circular economy perspective will be analyzed, looking at end-of-life strategies that aim to improve the circular flow of tire materials.

5.1 REDESIGN

The starting point of the circular economy is based on the redesign of the products and services themselves, taking into account the environmental consequences. The main objective of these models has so far been focused on aspects leading to the reduction of fuel consumption and, consequently, polluting emissions, while maintaining road safety. Some examples of new tire concepts are shown in 5-1. Figure.



5-1. Figure_ Innovative tire concepts and designs [51]

The next challenge is to reduce tire design to individual components or elements to facilitate tire repair or disassembly and reuse in the manufacture of new ones [52].

These new models have resulted in innovative products, some of which are already on the market. Airless or non-pneumatic tires that do not deflate use three-dimensional structures to support the weight of the vehicle. Goodyear markets airless tires for lawn mowers, while Michelin offers a line of airless radial tires for construction, recreational and small-scale utility vehicles. Cooper was active in the development and evaluation of non-pneumatic tire technology for military use. Hankook, Bridgestone, Michelin and Goodyear introduced concept tires that would bring airless tires to the automotive market. One example is Michelin's Tweel tire, an integrated airless tire and wheel assembly where the rubber tread is fused to the wheel core with polyurethane spokes. The Tweel tire aims for levels of performance beyond what is possible with conventional pneumatic know-how thanks to its tread design, additional suspension and reduced rolling resistance [53]. Michelin also introduced the Vision, a 3D printed biodegradable smart tire made using sustainable materials. It is airless and equipped with sensors that provide real-time updates on the condition of the tire [54].

Another line of innovation and redesign considers self-sealing tires. This technology involves the use of a sealing material placed as an inner layer under the tread. When a puncture occurs, the sealant prevents loss of air pressure by filling the hole. In addition, run-flat tires can safely travel up to 80 km at 80 km/h even after a tire loses pressure due to a puncture, according to the manufacturers' specifications. This feature allows drivers to navigate to a safe and convenient location to repair or replace the damaged tire.

Run-Flat tires also eliminate the need for occasionally used spare tires and rims, conserving materials and freeing up trunk space. Tires can lose about 3–6% of pressure per month without the driver's knowledge. Deflated tires can cause up to a 4% increase in fuel consumption while reducing tire life by 45% so many manufacturers are developing sophisticated and inherent detection systems (chips, tags or sensors) that, integrated into -a tyre, can transmit real-time information on pressure, tire temperature and tread wear, fault warning.

Goodyear has implemented so-called self-inflating tires, meaning a sensor/pump combination built into the tire structure, that could eventually eliminate the need for drivers to manually check tire pressure. Another example is the Tire Pressure

Monitoring Sensor (TPMS), an electronic device that alerts drivers when a tire is punctured or inflated below a threshold. This feature improves safety by improving traction, vehicle handling, lowers fuel consumption, increases braking efficiency, reduces tire wear and extends tire life. Potential applications as sensors through the combination of rigid conductive fillers and flexible and insulating matrices can also be derived from the development of electrically conductive elastomeric compounds. Various studies already published have addressed the detection of tension, compression and damage.

Incorporating sophisticated and inherent sensing systems as well as innovative concepts and designs into the tire remains a challenge. In an ideal context, products should be designed not only based on performance and aesthetics, but also on other key aspects derived from their subsequent management. They should be designed to be easily repaired, to be able to adapt to the new needs of the customer, and when they can no longer be useful, they should allow simple reuse in other production processes. When product design takes these concepts into account, the next links in the circular economy chain will be more easily developed.

5.2 RENEWAL - MANUFACTURING TIRES FROM RENEWABLE RESOURCES

The objective of manufacturing tires from renewable resources is to achieve sustainability but also to reduce dependence on fossil fuels. Natural rubber has unique properties of strengthening, resistance to tearing, impact and abrasion, among others. However, the supply of natural rubber from the Pará rubber tree (Hevea brasiliensis) cannot meet the growing world demand and thus new sustainable alternatives are being sought. The two main sources of alternative rubber crops are the Russian dandelion and guayule (Parthenium argentatum) [[55]]. Russian Dandelion is a fast-growing resource that produces large amounts of biomass, making it a strong alternative to the Pará rubber tree. Natural Russian dandelion rubber has excellent chemical and physical properties, and tires made from it can be as durable as Hevea. However, RDNR has a potential drawback as it contains several associated proteins that can lead to allergic reactions, limiting its use to non-medical applications. On the other hand, guayule natural rubber (GNR) has a structural backbone with 99.9% poly(cis-1,4-isoprene) units and molecular weight and physico -mechanical properties analogous to natural rubber. GNR also undergoes the same degree of strain-induced crystallization of natural rubber; however, its tensile strength is slightly lower. Another approach to achieving durability is to provide substitutes for other tire components such as fillers.

The main tire industries are aware of all these developments and implement components based on bio- resources in their production. Bridgestone [56] and Goodyear [57] include soybean oil as a natural ingredient in tire tread compounds, replacing traditional petroleum oil. Firestone markets agricultural tires with 10% soybean oil, which increases tread life by 10% and reduces petroleum oil use by up to 8.5 million gallons/year [58]. Pirelli and Goodyear report using silica derived from rice husks to produce tires with improved rolling resistance. Yokohama uses orange oil, derived from orange peels, instead of petroleum in tires, increasing fuel economy, reducing rolling resistance while maintaining good traction. Material experts and engineers at Continental have initiated a discreet transition to the year 2050, when all tires will be made from sustainable materials. Among the raw materials that will be used in the future in the manufacture of tires are agricultural waste - such as rice husk ash, dandelion rubber, recycled rubber or PET bottles [59].

5.3 REDUCTION

Downsizing is the optimal use of materials, and the tire industry primarily aims to reduce the weight of tires to reduce overall vehicle weight as well as to achieve fuel economy. One possible approach is to replace the carbon black with other filler materials in lower proportions and/or densities. Studies in the field of rubber nanocomposites have shown that other forms of carbon, including graphite, graphene, graphene oxide, and carbon nanotubes can be considered effective substitutes [60, 61, 62]. These carbon additives with various morphologies have remarkable properties, namely high electrical and thermal conductivities.

One of the biggest challenges in the tire industry is designing rubber tread compounds with improved rolling resistance and without compromising performance in terms of abrasion resistance and wet grip. Tires must perform effectively in different conditions, on dry, wet or snow-covered surfaces, and at the same time have acceptable wear resistance, low noise and good ride quality. Among the properties considered in tire development, these three main properties form the "magic triangle", well known in the tire industry.

Reducing rolling resistance is an effective way to reduce fuel consumption and CO2 emissions. When a tire rolls on the road, mechanical energy is dissipated as heat due to friction, which is known as rolling resistance [63]. Therefore, rolling resistance plays a major role in increasing vehicle fuel consumption. It depends on the type of tire, the nature of the running surface and the operating conditions, i.e. inflation pressure, load and speed. The environmental benefit of tires with low rolling resistance is driving the demand for such products worldwide, with a particular focus on understanding and modeling these properties.

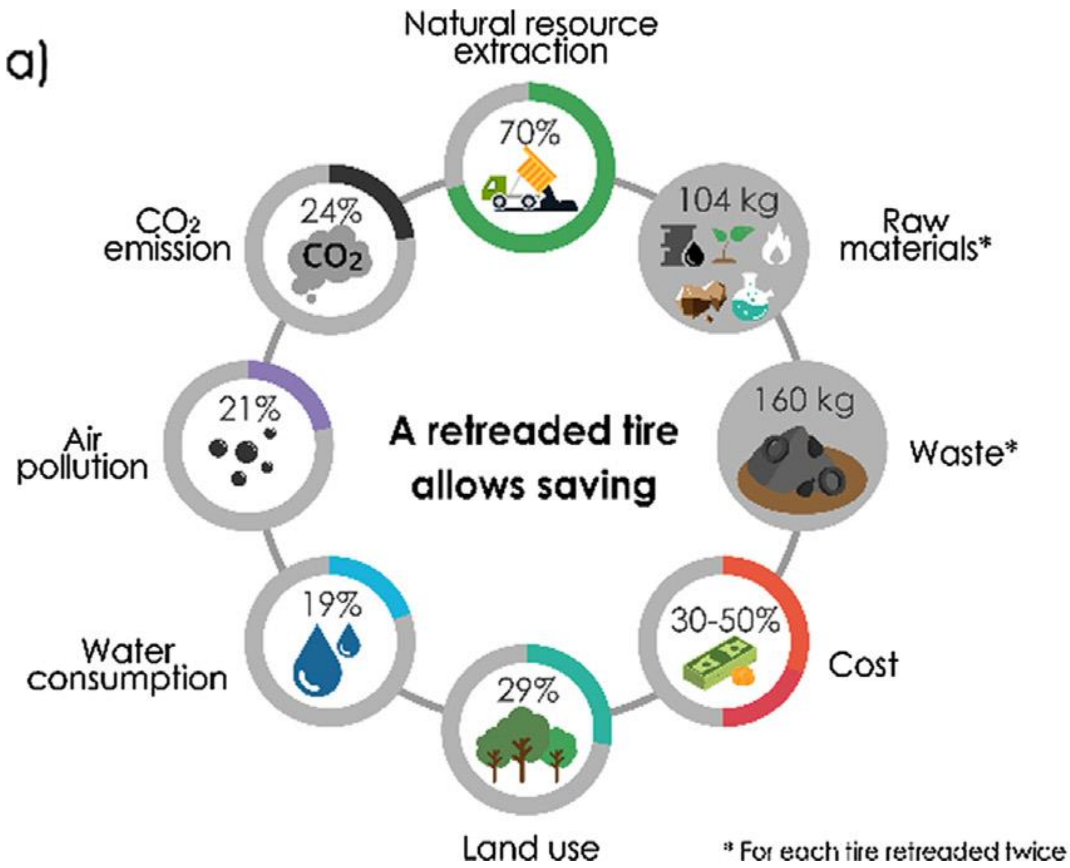
This tire is safe and antistatic and has low fuel consumption. In addition, abrasion resistance and thermal conductivity are extremely high [64]. On the other hand, Gratomic is developing graphene-enhanced tires to increase their strength and reduce friction. Graphene- enhanced Gratomic tires show over 30% increase in wear resistance compared to " premium tires " from other well-known commercial brands. Tests based on industry standard Dynamic Mechanical Analysis (DMA) showed a significant improvement in rolling resistance, indicating a more than 30% improvement in fuel economy. Wet and icy braking distances have also been improved by 40% [65]. Several tire manufacturers have developed green technologies that can reduce CO2 emissions. Bridgestone has developed Ecopia tyres, which reduce the carbon footprint of cars by offering exceptional low rolling resistance, excellent fuel economy and reduced replacement frequency. Continental tires, with EcoPlus technology [66], and Firestone technology Fuel Fighter [67] are focused on reducing rolling resistance while increasing grip on wet surfaces and improving tread life. Also, Beijing Tiancheng Company Linglong Tire is working on developing graphene rubber compounds for fuel efficient tires.

5.4 REUSE

Reuse includes the sale of partially used tires for domestic road use and other purposes, as well as for export to other countries where the road use conditions are less restrictive.

5.5 RETREADING

Retreading is the process of replacing the worn tire tread with a new one, thereby reducing waste and limiting the use of resources and reducing CO2 emissions. It is a safe, cheap and ecological solution. The practice of retreading is a perfect example of the circular economy and resource efficiency in practice. Retreading reduces approximately 160kg of waste for every tire retreaded twice and saves 104kg of raw materials, all while achieving CO2 savings.



5-2. Figure_The main benefits and savings of a retreaded tire[52]

5.5.1 THE PNEUSOL PROCESS

Non-reusable used tires represent waste with excellent mechanical properties that are available in significant quantities in many countries. Pneusol ® involves the association of two elements: non-reusable used tires ("tyre") and earth ("soil"), be it natural, artificial or filling from other waste. This association not only capitalizes on significant volumes of non-reusable used tires, but the resulting soil ("tyresoil ") is one with superior mechanical properties.

5-3. Figure_Pneusol [52]

Construction works that resort to this procedure involve the construction of: support structures with large slopes (walls anti-avalanche or to prevent landslides); light fillings (embankments, slopes, foundation land) that reduce direct pressures by up to 40%; safety systems for shores, various military applications, etc.

Pneusol ® benefits: Reduced costs of embankment and/or damming due to the replacement of concrete and/or other materials used for this purpose with used tire waste; The same durability and stability over time is ensured as with the use of classic methods and products because the vulcanized rubber in the tires has an extremely long period of self-degradation.

5.6 REPAIR

Repair is part of the principles of the circular economy that contributes to extending the life of products, allows savings in raw materials and energy and helps to reduce waste.

Tires can be repaired in many cases, for example, when they are deflated, for various reasons: puncture, loss of pressure, when the affected part is on the tread of the tire.

The classic variants used for repairing tires: with pad, with patch, with pad and patch.

One technology that deserves attention is the development of self-healing materials. This class of smart materials offers the possibility to increase their useful life and therefore helps to lower the environmental and economic costs of future materials [[68]].

Self-healing rubbers have expanded rapidly globally with the development of new concepts and strategies in academic and industrial laboratories.

Self-healing materials are generally grouped by healing mechanism into two main categories: **extrinsic and intrinsic.**

In extrinsic self-healing materials, a so-called healing agent is contained in discrete particles (capsules or fibers) embedded in a polymer matrix and released upon damage.

The discrete healing agent is consumed in the healing reaction and therefore healing is limited to a single event.

On the other hand, intrinsic self-healing polymers use fragments that become an inherent part of the material itself. Intrinsic self-healing can be achieved by promoting physical interactions and/or the formation of dynamic chemical bonds between the interfaces of a damaged area (crack).

Puncture-free (self-healing) rubber contains a dense, sticky material that automatically seals the hole in the event of a puncture. The material prevents or reduces further pressure drop. Puncture-free tires are usually marked SEAL [[69]].

However, achieving such repair in tires is particularly difficult, as cross-linking restricts the polymer chains to form new bonds in previously (pre)damaged areas. Various reversible dynamic groups such as hydrogen bonding and ionic interactions have attracted increasing attention in the field of self-healing rubber.

Moreover, the combination of different self-healing mechanisms (mostly intrinsic) is currently emerging as a strategy to provide an optimal compromise between mechanical performance and reparability. Although this field of research is growing and attracting worldwide attention, self-healing rubbers are still far from being acceptable for use in the tire industry due to their low mechanical strength.

The addition of reinforcing fillers and/or the combination of different healing strategies is seen as a way forward to improve the overall mechanical performance of self-healing rubbers without compromising their repair capacity.

5.7 RECOVERY

Recovery: transforms a waste into energy or fuel, which can be reintegrated into the economic flow as a substitute resource for the use of other energy sources.

Energy and material recovery offers a complementary alternative to address tire waste issues and achieve sustainable development goals following the principles of the circular economy.

Thermo -chemical conversion technologies transform used tires into valuable chemicals, fuels and energy [[70]]. These techniques are particularly useful for ELT and do not depend on the quality or type of tire [[71]], offer an environmentally attractive way to reduce the accumulation of waste tires and represent a valid alternative for a reusable product by converting used tires.

Reduction of waste volume by more than 90% and net energy recovery with possible material recovery are the main advantages of these methods. However, generation of toxic gases and disposal of ash are some problems associated with these heat treatments.

5.8 TIRE PYROLYSIS

Pyrolysis consists in the thermo-chemical decomposition (400–1200 ^{0} C) of organic compounds in low molecular weight products at reduced or normal pressure and under an inert atmosphere, preventing oxidation and changes in phase or chemical composition. Through the pyrolysis process, all types of tires, including agricultural tires (for which there are currently no solutions) will be decomposed in an oxygen-free, zero-pollution environment into: gas, pyrolysis oil and recycled coal. Tire pyrolysis technology is sustainable due to low energy consumption, lack of polluting emissions and waste water, being a closed system in which used tires are 100% recycled without producing any other waste or production residues. The process is self-sustaining, without consuming other resources.

Table 5. 1. Summary of tire pyrolysis processes [[72]]

Pyrolysis Process _	Recovery Type	Outputs	Cost Energy	Benefits	Disadvantage	Impact on environment
Pyrolysis fixed bed reactor	Chemical	Gas, pyrolysis oil and coal recycled.	Low	operating simplicity	Working interrupted	Maximum
Pyrolysis fluidized bed reactors	Chemical	Gas, pyrolysis oil and coal recycled.	Low	Operation keep going	Projection and operation complexity and investment costs _ HIGH	Maximum
Pyrolysis oven rotary	Chemical	Gas, pyrolysis oil _ and coal recycled.	Low	Easy to control differently aspects of the operation	Slow pyrolysis	Maximum

5.9 RECOVERY ENERGY

The fuel derived from tires (Tire derived fuel TDF), one of the main options for ELT, is mainly used in cement kilns, but also in thermal power plants, pulp and paper mills, steel mills and industrial boilers. In Europe, the cement sector is the main use of TDF. Furnaces are increasingly equipped to use ELTs as supplemental fuel and are still in compliance with 2008 air emission standards. Tires have a high energy content and are an equal or better energy source than many other solid fuels. This, along with rising energy costs and increased environmental awareness in recent years, has led to an increase in the use of TDF. The infrastructure exists and with sufficient support and recognition of TDF as a viable alternative, industry development has significant potential. TDF is currently the largest use for ELT in the US and Japan, and energy recovery is roughly equal to material recovery in Western Europe and the US.

Tires have a high energy content and PTO is an equal or better source of energy than other fuels:

Table 5.2 Energy content and CO_2 emissions of fuels

Combustible	Energy (Gigajoule /ton)	emissions	
		$kgCO_2$/ton	$kgCO_2$/ Gigajoule
TIRES	32.0	2,270	85
Coal	27.0	2,430	90
Petroleum coke	32.4	3,240	100
DIESEL	46.0	3,220	70
Natural gas	39.0	1,989	51
Wood	10.2	1,122	110

5.10 RECYCLE

Recycling is keeping resources in the loop for as long as possible. It transforms a waste into a material that can be reintegrated into the economic stream as a substitute resource for the use of virgin resources. Tire recycling is defined as any material recovery operation of used tires, namely cutting, shredding, granulating, or any other operation that causes changes in the nature or composition of the used tire, through industrial processes, in order to obtain raw materials [73].

Recycling has the role of recovering materials that can be reused in various industries, but also to prevent the contamination of ecosystems and endangering the health of the population [74].

Table 5.3. Summary of tire recycling processes [75]

The recycling process	Recovery type	Outputs	Energy cost	Advantages	Disadvantages	Environmental impact
Ambient grinding	Mechanical	Granulated rubber crumbs of different sizes	High	Well known methods and most used.	Repeated grinding action to achieve uniform chip sizes	Minimum
Cryogenic grinding	Mechanical at very low temperature	Granulated rubber crumbs of	Medium	Finer particle size and better purity	Poor binding properties of rubber	Minimum

The recycling process	Recovery type	Outputs	Energy cost	Advantages	Disadvantages	Environmental impact
		different sizes		of cryogenically ground rubber	particles	
Wet grinding	Mechanical and waterjet	granulated rubber crumbs of different sizes	Medium	Finer crumb cleaner, more consistent rubber crumb than ambient grinding	the rubber particles need to be dried following grinding It cannot give high tensile properties	Minimum
Fixed bed reactor pyrolysis	Chemical	Gas, oil and char.	Low	Simple operation.	Interrupted operation.	Maximum
Fluidised bed reactors pyrolysis	Chemical	Gas, oil and char.	Low	Continuous operation	complex design and operation, and high investment cost	Maximum
Rotary kiln pyrolysis	Chemical	Gas, oil and char.	Low	Easy to control different aspects of operation.	Slow pyrolysis	Maximum

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