Circular Economy and Competitiveness of the European Road Transport

Strengthening sustainability and resource sovereignty of the automotive industry

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Circularity and Competitiveness

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Acknowledgement

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Executive Summary

The document titled "Circular Economy and Competitiveness of the European Road Transport" emphasizes the urgent need for the automotive industry to transition towards a circular economy (CE) to enhance sustainability and resource sovereignty complementing the efforts towards zero-emission road transport. It defines the CE model as one that promotes the continuous reuse, repair, and recycling of materials, contrasting sharply with the traditional linear economy characterized by a take-make-dispose approach. The document highlights the significance of the 9R principles—Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Recycle, and Recover—as essential strategies for implementing a circular economy. The automotive sector currently faces significant challenges, including high material consumption, low vehicle-to-vehicle recycling rates, substantial scope 3 upstream CO_2 emissions, and a dependency on non-EU resources.

The EU's reliance on material imports (particularly but not only for zero-emission vehicles), the pressing need for improved resource productivity, and to reduce the carbon footprint are identified as critical issues that must be addressed. In response, the European Commission has introduced various strategies and regulations aimed at enhancing circularity including new battery regulations and proposals for stricter vehicle design and end-of-life management. These initiatives are designed to modernize existing legislation, reduce the environmental impact associated with vehicle production and disposal, and improve access to recycled materials.

The document outlines several research priorities essential for advancing the circular economy for zero-emission vehicles within the automotive sector. These include the development of sustainable materials and innovative recycling technologies, improvements in product design for circularity, and enhancements in reverse logistics and dismantling processes. Additionally, it emphasizes the importance of digital solutions for tracking, tracing, and managing products, components, and materials throughout their lifecycle.

The automotive industry plays a pivotal role in driving economic growth and innovation in Europe, contributing significantly to the region's GDP and employment. By enhancing vehicle circularity, the sector can generate broader benefits that extend to other industries. Achieving a true circular economy requires collaboration across various sectors, including manufacturing, energy, finance, and waste management. This integrated approach is essential for optimizing resource recovery and minimizing environmental impacts. In conclusion, the document advocates for a comprehensive transition to a circular economy in the automotive sector. It underscores the necessity for innovative research, supportive policies, and cross-sector collaboration to effectively address environmental challenges and enhance the competitiveness of the industry. Interlinked with the transition towards zero-emission road transport, circular economy will become a competitive edge for Europe.

The roadmap addresses a two-layer approach for future research and innovation programs at both European and national levels:

Firstly, it proposes three large-scale, industry-led lighthouse projects on European level (Fossil Free Automotive Polymers, Transcontinental Recycling System and Recycling Factory of the Future) that should be managed with continuous attention and support at the highest possible level with ample funding

supported by the best available project management practices and capable human resources, following a similar way to China's Road-and-Belt Initiative, and the USA's the Lightspeed and Stargate projects. The rationale for focusing efforts on these projects is straightforward: only by deploying substantial private and public resources in the multibillion-euro range the EU will be able to leapfrog circularity and competitiveness to the next level in a timely manner. These projects should be integrated into the Next Framework Programme ("FP10").

Secondly, these large projects should be complemented by smaller and highly connected initiatives and projects on national and/or European levels that focus on specific research and innovation needs. These projects should be embedded as soon as possible in national and/or European public, academic, and corporate research and innovation frameworks.

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1 Introduction

The Circular Economy (CE) describes a new approach of utilizing resources keeping material flows and products as much as possible in a circle. The European Commission defines the CE as follows [1]:

> *The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. … When a product reaches the end of its life, its materials are kept within the economy wherever possible thanks to recycling. These can be productively used again and again, thereby creating further value. This is a departure from the traditional, linear economic model, which is based on a take-make-consume-throw away pattern. This model relies on large quantities of cheap, easily accessible materials and energy.*

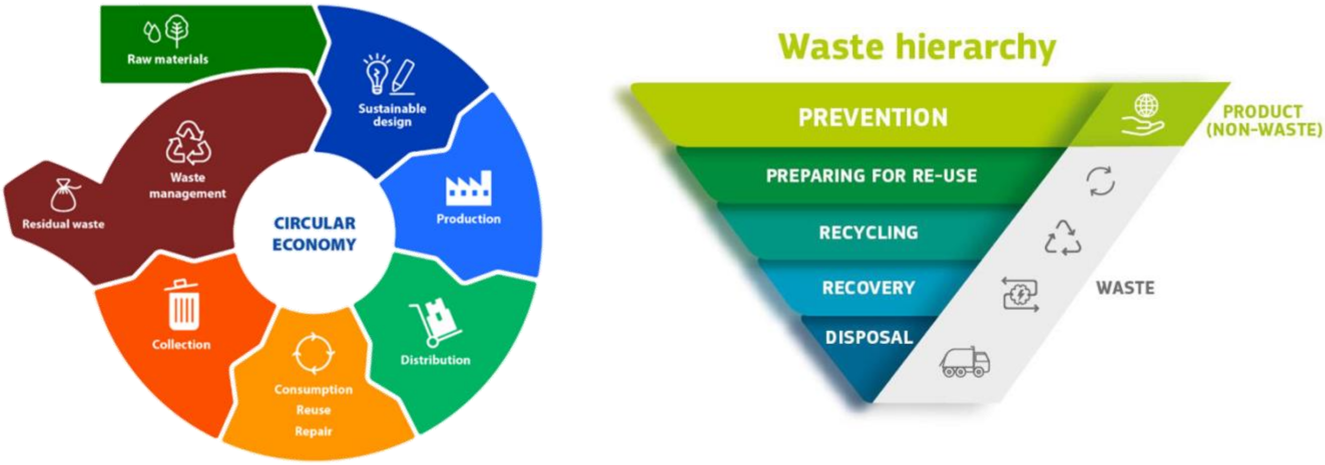

Figure 1: Left: The circular economy model [1], right: The Waste hierarchy [2]

Consequently, the Circular Economy impacts all stages of a product life cycle from material sourcing till various End-of-Life strategies. Within this context, CE practitioners refer usually to the so-called 9R-principles (see Fig. 2) to be applied in the various product life cycle stages.

Circular economy ↑ Increasing circularity ↓ Linear economy		Strategies	
	Smarter product use and manu-facture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
		R1 Rethink	Make product use more intensive (e.g. by sharing product)
		R2 Reduce	Increase efficiency in product manufacture or use by consu-ming fewer natural resources and materials
	Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
		R4 Repair	Repair and maintenance of defective product so it can be used with its original function
		R5 Refurbish	Restore an old product and bring it up to date
		R6 Remanufacture	Use parts of discarded product in a new product with the same function
		R7 Repurpose	Use discarded product or its parts in a new product with a different function
	Useful application of mate-rials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
		R9 Recover	Incineration of material with energy recovery

Figure 2: The 9 R principles [3]

The transformation of the European Industry towards a circular economy is seen as essential not only to meet the targets of the green deal but also has the potential to boost competitiveness particular for the automotive sector. However, the current impact of a CE on the Green Deal and the European Competitiveness based on the Eurostat data [4] and the European Monitoring Framework [4, 5] is still limited.

In terms of sustainability the EU consumption footprint increased by 4% between 2010 and 2021. Between 2018 and 2023, Europe consumes about 500 GT material equivalent to about 18% of the accumulated use of materials since 1900. At the same time, the use of secondary materials dropped from 9,1% in 2018 to 7,2% in 2023. With respect to European's resource sovereignty, the EU's material import dependency was 22.9% in 2021 while depending on 52% of metal ores and 71% of fossil-energy from outside the EU. Despite that, the resource productivity of the EU economy increased by about 45% since 2020, indicating progress in decoupling economic growth from resource use.

In terms of competitiveness and innovations, private investments in economic sectors relevant to the circular economy reached EUR 121.6 billion in 2021, equivalent to 0.8% of the EU's GDP. The circular economy employed 4.3 million people (full time equivalent) in 2021, an increase of 11% compared to 2015. In the same period, the added value in the circular economy sectors increased by 27% compared to 2015 reaching EUR 299 billion.

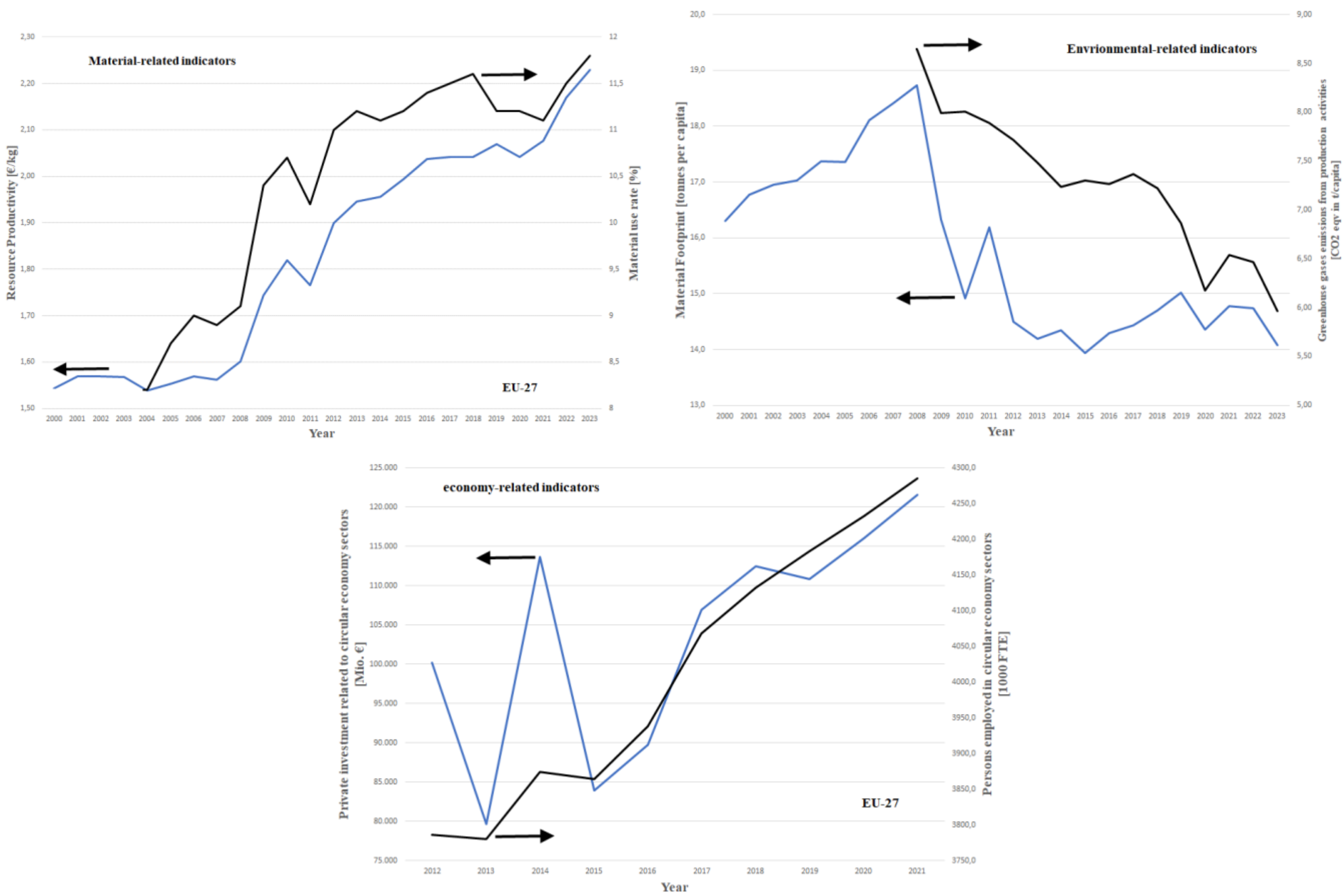

Figure 3: Circular Economy Indicators for the EU-27 [4]

1.1 Policy context, challenges and objectives

The European Commission has a dedicated strategy and action plan to enhance the circularity in Europe [6]. Part of this strategy is the new battery regulation [7] and a CE monitoring framework [4]. The latter proposes, among others, as circularity indicator the material footprint (t/capita), the resource productivity (GDP/DMC[1]) and circular material use rate (%) (see Fig. 3). Furthermore, the private investment related to circular economy sectors as percentage of gross domestic product (GDP) is proposed as indicator.

On July 13, 2023, the European Commission released its proposal for stricter regulations focused on the circular design of vehicles and the disposal of end-of-life vehicles, aiming to replace the current framework [8]. The proposal introduces measures to enhance the circularity of the automotive industry across vehicle design, production, and end-of-life management. The primary goal is to modernize existing EU legislation, optimize the functioning of the EU internal market, reduce the environmental impact of vehicle design, production, use, and disposal, and support the sustainability of both the automotive and recycling industries.

The revision of the ELV directive defines specific recycling rates only for plastics. The revision foresees that 25% of the plastic content in a vehicle must come from secondary sources of which 25% must come from the recycling of ELVs (closed-loop recycling)[2]. Targets for other materials (steel, aluminium, CRM) are not provided but the commission will be empowered to define targets in the future including target levels calculation and verification rules. Furthermore, the ELV directive defines an extender producer responsibility (EPR) obliging the (automotive) producer to set-up a collection system and to ensure authorized treatment facilities. Although the EPR is beyond the focus of this document, it defines boundaries and constraints to be considered while implementing a circular economy.

Circular Economy is furthermore addressed in the European Strategy on Sustainable and Smart Mobility [9]. The strategy foresees synergies with the circular economy transition, “in particular by applying product-as-service solutions to reduce virgin material consumption, use sustainable alternative transport fuels, optimise infrastructure and vehicle use, increase occupancy rates and load factors, and eliminate waste and pollution” [6].

Moreover, a 25% recycling benchmark has been set in Europe´s Critical Raw Materials (CRM) Act [10]. The promotion of raw material recycling and the establishment of a robust secondary market are essential. This can be accomplished by supporting the recovery of critical raw materials from waste and enhancing efforts to reduce negative impacts on labour rights, human rights, and environmental protection. Additionally, certification schemes aimed at improving the sustainability of critical raw materials within the EU market should be acknowledged.

The assessment of the environmental footprint by means of an LCA is part of the circular economy framework as well. On their European Platform on LCA | EPLCA the EC states that “the PEF and OEF[3] are the EU recommended Life Cycle Assessment (LCA) based methods to quantify the environmental impacts of products (goods or services) and organisations” [11]. On that platform also recommendations

[1] GDP = Gross domestic Product, DMC = Direct Material Consumption
[2] While elaborating this roadmap, the European Parliament is discussing a lower quote of 20 % and 15% closed loop materials.
[3] PEF = Product Environmental Footprint, OEF = Organisation Environmental Footprint

can be found how to conduct a PEF and OEF. However, a transport-specific LCA and common CE criteria are still lacking harmonisation.

1.2 Importance of Circular Economy research and innovation

Research and innovation in the context of the Circular Economy is crucial for Europe as it seeks to tackle the pressing environmental, economic, and social challenges of the 21st century. Europe is facing significant issues such as resource depletion, resource dependence for sourcing outside of the EU zone, waste accumulation, and the urgent need to combat climate change. Adopting a circular economy model where products, materials, and resources are continually reused, repaired, and recycled can help address these challenges, but making this transition requires substantial innovation, scientific knowledge, practical solutions and their fast implementation.

Research and innovation at European level play a pivotal role in driving the circular economy forward by developing new technologies, materials, and processes that enable more sustainable production and consumption. For example, scientific advancements are necessary to improve reverse logistic processes, to enhance recycling technologies such as dismantling or sorting, increase the efficiency of resource recovery, and develop new biodegradable or recyclable materials. Research and innovation also support the design of longer-lasting and more resource-efficient products that can be easily repaired or repurposed, reducing the need for raw materials and minimizing waste.

Furthermore, research is essential for informing policymaking at the EU level. In order to create effective and evidence-based policies that support the transition to a circular economy, reliable data and innovative solutions are needed. Research helps policymakers understand the economic, environmental, and social impacts of different circular economy strategies, enabling them to implement the most effective measures for industries, consumers, and the environment. This ensures that the shift towards a circular economy is both feasible and beneficial for all sectors of society.

One of the key benefits of research and innovation at the European level is the potential for collaboration across borders. Europe consists of many different countries (EU27 + 20), each with its own challenges, opportunities, and strengths. By pooling resources, expertise, and knowledge through collaborative research projects, Europe can develop innovative solutions that work across national borders and can be implemented at scale. These collaborations also help share best practices, ensuring that all countries in the EU can benefit from the latest advancements in circular economy research.

In addition to driving environmental sustainability, research and innovation in the circular economy also has significant economic and job creation potential. By fostering innovation in green technologies, resource management, and sustainable business models, research can stimulate new industries and opportunities for growth. The transition to a circular economy has the potential to create thousands of new jobs in sectors such as waste management, renewable energy, and sustainable manufacturing. Research helps to ensure that these sectors are well-equipped to meet the growing demand for green solutions and technologies. This goes hand in hand with lower total cost of ownerships (TCO) of zero-emission vehicles, through lower product costs avoiding costly primary material sources and lower CO_2 footprint resulting in lower CO_2 prizing, among others.

In conclusion, research is essential to the success of the circular economy in Europe. It enables technological innovations, informs policy decisions, fosters cross-border collaboration, and contributes to economic growth. By investing in research, Europe can accelerate its transition to a more sustainable, resource-efficient, and competitive economy, helping to achieve its climate goals while ensuring a cleaner and more resilient future for all.

1.3 Role of the road transport sector/industry

The automotive industry is a cornerstone of the European economy. Since many decades it plays a key role in driving economic growth, innovation, and prosperity across Europe, contributing nearly 7 percent to the region's GDP. It provides direct and indirect jobs to around 13 million Europeans. Each year, around 10 million new vehicles are sold in the European Union, while 6 million are scrapped after being collected, depolluted, and dismantled. The current processes and business models of the circular economy within the EU already produce millions of parts that can be refurbished or directly reused, as well as millions of tons of valuable recycled materials.

Vehicle circularity plays a significant role in achieving the EU Green Deal targets and in driving new technologies, profitable business models, and resource autonomy, all of which would further improve the current situation. It is expected that further enhancing vehicle circularity will generate significant spillover effects, boosting the circularity of other industries and, ultimately, of the European Union as a whole. Compared to other industries, automotive circularity is already highly regulated and achieves high rates of component reuse and material recycling. Directive 2000/53/EC of 18.09.2000 and Directive 2005/64/EC (applicable to vehicle category M and N) of 26.10.2005 (the so-called 3R type-approval) encourage the refurbishment and reuse of vehicle components such as engines, transmissions, tires, and electronic parts that are still functional. They also promote the recycling of materials like metals, plastics, glass, and rubber.

The end-of-life materials of vehicles must be processed for recycling to meet clearly defined material recycling rates. Waste that cannot be directly recycled can be used for energy recovery, generating heat or electricity. Current regulations require automakers to be accountable for the entire lifecycle of their vehicles, including proper disposal when the vehicle reaches the end of its life. Additionally, these regulations demand the establishment of ELV take-back schemes, where manufacturers must facilitate the collection and disposal of end-of-life vehicles.

The establishment of a circular economy within the transport sector needs intensive collaboration amongst OEMs, the supplier, the recycling, the logistics, the construction, the chemical, the agricultural, the raw material, the IT and many other industries. In comparison to electrification of vehicles the transformation necessity outside the automotive industry is much larger as much more different industries have to be involved (see Fig. 4). It is important that the policymakers support the need for intensive collaboration by setting the right framework within and across various industrial sectors. This framework must create a large, accelerating momentum towards the establishment of circular economy and stimulate increasing private investments at large scale.

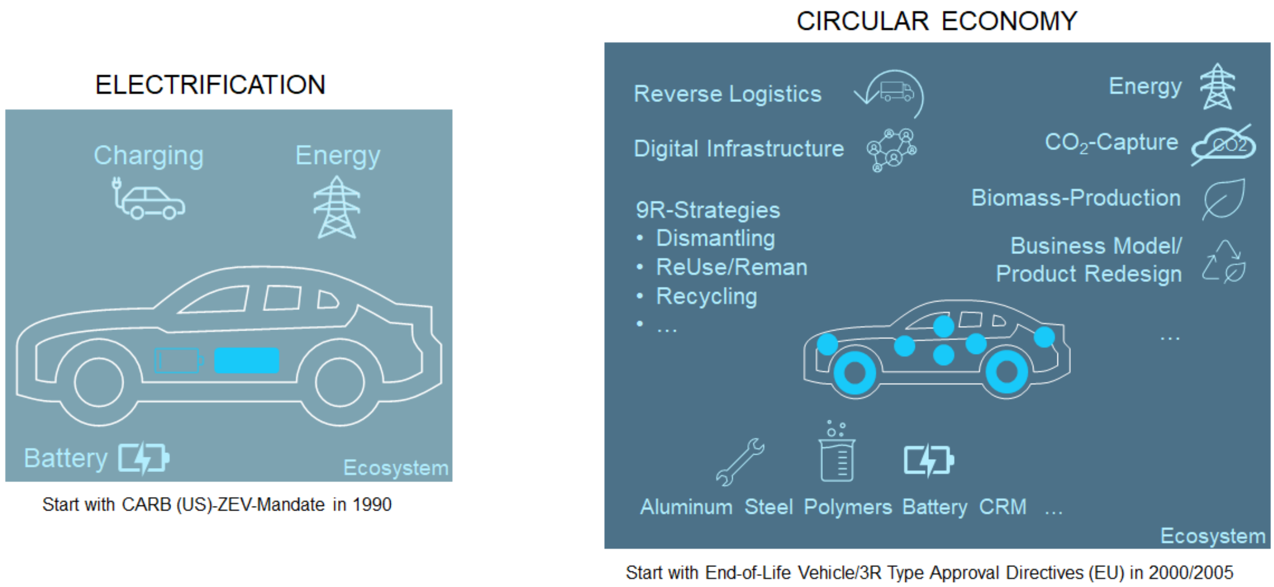

Figure 4: Transformation towards electrification vs. circular economy

1.4 Cross-sectorial aspects

A true circular economy goes beyond isolated efforts within individual industries, requiring cross-sectoral collaboration. By integrating various sectors such as material mining and production, manufacturing, energy, agriculture, finance, recycling, and policy, we can create a more efficient, sustainable system that promotes long-term resource recovery and reduces environmental impact.

Key sectors must work together to achieve circularity. For example, the manufacturing sector relies on sustainable sourcing from agriculture and mining, while renewable energy solutions are crucial for reducing carbon footprints in production and for creating polymers based on biomass or CO_2. Waste management systems depend on collaboration with manufacturers and technology sectors to improve recycling and recovery processes.

Financial sectors also play a critical role, as circular businesses often require different investment models. By working together, financial institutions, policymakers, and businesses can create funding mechanisms that support circular practices, such as green bonds or impact investments. Additionally, government policies must incentivize circular practices across industries and create an environment conducive to long-term sustainability.

Consumer behaviour is another crucial factor, where education and collaboration between sectors can drive more sustainable choices. Retailers, educators, and businesses must work together to raise awareness and encourage participation in recycling and sustainable consumption.

In conclusion, a true circular economy cannot be achieved by any single industry sector alone. Only through intensive collaboration across industries - manufacturing, energy, finance, waste management, and policy - can we build a system that is resource-efficient, regenerative, and sustainable for future generations.

2 Research Priorities

Within this chapter research priorities focussing on zero-emission vehicles are being discussed non-exclusively. The five areas identified are highly linked with each other and some overlaps cannot be avoided but should be seen from the perspective of each research priority.

The research needs are categorized in short term [2025 – 2030], medium term [2030 – 2035] and long term [> 2035] research needs. Furthermore, research need has been assigned to a lighthouse project where relevant with flags as follows: ❶: Fossil Free Automotive Polymers, ❷: Transcontinental Recycling System and ❸: Recycling Factory of the Future. The lighthouse projects are outlined in Chapter 3. If not flagged, the research need refer to classic collaborative research projects.

Although focussing on the vehicle it is recognised that research is also need on systemic or cross-cutting issues as well as on behavioural aspects such as

- impact of mobility concepts on circular economy approaches,
- reverse logistics for End-of-Life vehicles (ELV),
- societal acceptance or
- skill development.

These aspects will be addressed either in the intended lighthouse projects (see chapter 3) or will be elaborated in a revision of this document since it is considered as “living” roadmap.

2.1 Materials and Material Recycling

This chapter focusses on material recycling and related research needs. Vehicle technology relies on specialized metals like high-strength steels and aluminium, but closed-loop-recycling is currently hindered by contamination. The same problem applies to magnets and other critical raw materials. Moreover, the automotive industry seeks to replace fossil-based polymers with non-fossil-based alternatives while addressing challenges in recycling. Per- and polyfluoroalkyl substances (PFAS) pose environmental risks, prompting research into safer substitutes and redesign strategies. Key research needs include improving recycling processes, developing new materials, and enhancing circular economy practices balancing different aspects such as disassembly, mono material design or design out pollution.

<u>State of the Art</u>:

Vehicle technology relies heavily on specialized materials that must meet high standards of durability, strength, and weight optimization. High-strength steels and aluminium are critical, but their recycling is often hampered by contamination from tramp elements like copper and nickel. The recycling process typically involves shredding vehicles and other scrap sources, which can introduce impurities that degrade material quality (investments by the European metal scrap industry to produce cleaner grades).

Magnets, Critical Raw Materials (CRM), and Rare Earth Elements (REEs) are essential for modern automotive technology, particularly in electric vehicle (EV) motors, batteries, and electronic systems. The development of forementioned components focuses on improving efficiency, reducing reliance on scarce resources like neodymium and dysprosium, and enhancing sustainability through alternative materials. Currently, recycling of these materials in cars is still in its early stages but gaining traction. Processes for recovering REEs from end-of-life EV motors and electronics are being developed, with research focusing on more efficient and cost-effective methods. While battery recycling is more advanced, the recovery of permanent magnets and other components containing CRM remains a challenge due to complex separation processes. Efforts are underway to establish closed-loop recycling systems to reduce dependency on raw material extraction (which takes place mostly outside of Europe) and lower environmental impact. However, the quality and costs of recycled materials do not meet the needs of the automotive industry particular for electrified vehicles.

Polymers, predominantly derived from fossil fuels, contribute significantly to greenhouse gas emissions when disposed of improperly. The automotive industry is actively seeking to replace these fossil-based polymers with recycled-, bio- or carbon-capturing-based alternatives. Furthermore, the recycling of automotive polymer scrap is complicated by the presence of fillers and additives, which can hinder the recycling process, and the use of multiple plastic materials in components and across organisation that are not compatible. With the increase of EVs in the fleet, the use of polycarbonates and polyamides is expected to grow [12].

PFAS, widely used in automotive applications for their chemical resistance and durability, pose environmental challenges due to their persistence in the environment and potential health risks. The anticipated classification of additional substances as harmful under REACH could complicate recycling efforts, necessitating the development of new processes to safely extract and manage these materials.

<u>Challenges</u>:

The circular economy is crucial for sustainability and material supply security, sovereignty and resilience, emphasizing closed-loop recycling of materials, which leads to:

- Minimised environmental impact,
- Reduced energy consumption and Greenhouse Gas (GHG) emissions,
- Strengthened local economies and resilient supply chains,
- Access to (critical) materials within the EU without geopolitical risks,
- New business opportunities with growth potential.

However, the diversity of metal alloys, plastics, and composites in transportation complicates recycling processes and affects scrap quality. Current shredding and sorting technologies need improvement to enhance productivity and reduce impurities that hinder reuse and recycling. Developing purification technologies and designing materials tolerant to residual elements are essential for optimizing scrap quality. Dismantling specific components, like e-drives and power electronics, can also improve scrap quality, particularly for critical raw materials (CRM) in delicate components.

The steel industry is transitioning to electric arc technology, allowing for over 20% secondary material content, with hydrogen being explored to further reduce CO_2 – or in general GHG – emissions. Additionally, aluminium's CO_2 footprint can be minimised through process optimizations, such as using inert anodes.

Most polymers are derived from crude oil, presenting challenges in reducing fossil feedstock. Mechanical recycling is already a solution for plastic circularity. However, these recycled polymers have intrinsically lower properties than virgin (downcycling). Alternatives include physical recycling, chemical, and enzymatic recycling technologies, which can produce secondary raw materials with properties similar to virgin materials. These processes require advancements for high-volume throughput and competitiveness.

To decarbonize the automotive sector, secondary polymer resources, like consumer scrap, should be evaluated to reduce environmental pollution. Bio-based materials could offer a sustainable alternative to crude oil-based products, but challenges such as varying material properties and natural decomposition resistance need to be addressed in future research. Scaling up startups and qualifying supply chains for bio-based materials is seen as a significant opportunity for enhancing sustainability in the road transport sector.

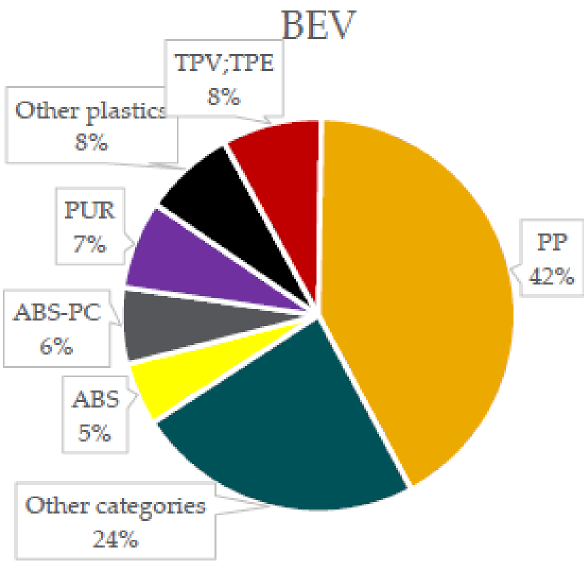

Figure 5: Top six plastic and elastomer categories of the averages of all BEVs [13].

<u>Research Needs</u>

- <u>**Steel / Iron and Aluminium:**</u>

  ➢ **(Semi-)Automated Dismantling Before Shredding:** ❷❸ *medium term]*
  Develop methodologies for efficiently dismantling vehicles before **shredding** to minimize contamination from tramp elements. This could involve creating specialized tools and training for workers to disassemble vehicles safely and efficiently.

  ➢ **High-Efficiency Scrap Metal Sorting Processes:** ❷❸ *[short term]*
  Invest in advanced sorting technologies, such as AI-driven optical sorting and magnetic separation, to improve the quality of recycled metals and reduce costs. Research should focus on optimizing these technologies for different types of metals and alloys.

  ➢ **Zero-Emission Processing:** *[long term]*
  Explore renewable energy sources for metal processing, including solar and wind energy, to reduce the carbon footprint of metal recycling operations. This may involve partnerships with energy providers to ensure a stable supply of green energy.

- **Development of Alloys:** *[medium term]*
  Research new alloy compositions that can tolerate higher levels of tramp elements without compromising performance. This could involve collaboration with material scientists to innovate new formulations.

- **Materials for Magnets:**

  - **New Materials for Magnets**: *[medium term]*
    Investigate alternative materials that can replace rare earth elements in magnets, focusing on the development of high-performance, cost-effective substitutes. This may include research into composite materials or novel magnetic materials.

  - **Disassembly Technologies**: ❷❸ *[medium term]*
    Develop semi-automated or automated disassembly technologies that can efficiently extract magnets from electronic components, ensuring minimal damage to the materials.

  - **High-Throughput Recycling Technologies**: ❷❸ *[medium - long term]*
    Research and develop recycling processes that can handle large volumes of magnet materials, ensuring that the recycling methods are economically viable and environmentally friendly.

- **Other Critical Raw Materials (CRM) and Rare Earth Elements (REE):**

  - **Use of Alternative Materials:** *[medium term]*
    Conduct research into alternative materials that can serve the same functions as critical raw materials, focusing on performance, cost, and availability.

  - **More Efficient Use in Applications:** *[short term]*
    Develop strategies to optimize the use of existing materials in applications, including lightweighting and design modifications that reduce material consumption.

  - **Research Regarding Secondary Material Use:** *[medium term]*
    Investigate the potential for using secondary materials in manufacturing processes, including the development of standards and guidelines for secondary raw materials quality enabling their incorporation into new products.

- **Polymers:**

  - **Improvement of recycled feedstock sorting and refining process**: ❸ *[short - medium term]*
    Research on developing technologies that allow to increase recycled feedstock purity and quality, ensuring that the majority of recycled materials can be valorised through mechanical recycling with the highest ability to maintain polymer quality.

  - **Bio-Based Polymers as Drop-In Solutions:** ❶ *[short - medium term]*
    Research the feasibility of using bio-based polymers derived from renewable resources, such as agricultural/forestry waste or algae (non-food competition), as substitutes for traditional fossil-based polymers. This includes developing production processes that are economically viable and scalable meeting automotive demands.

  - **Reduction of Polymer Variety**: *[medium term]*
    Promote the use of "monopolymer" designs that simplify recycling processes by reducing the

variety of polymers used in a single product. This could involve collaboration with designers and manufacturers to create standardized components.

- **CO_2 to Polymer (CCU/DAC) Technologies**: 1 *[long term]*
  Explore carbon capture and utilization technologies that convert CO_2 emissions into usable polymers, focusing on developing efficient catalytic processes.

- **Advanced and High-Throughput Recycling Technologies**: 2 3 *[medium - long term]*
  Invest in research to develop advanced recycling technologies that can process mixed polymer waste streams, ensuring that recycled materials maintain properties comparable to virgin materials taking into account of releases of micro/nano plastics which is part of the CE in the ISO 59000 standards.

- <u>**Innovative Bio-Based Materials:**</u>

  - **Automotive Qualification of Bio-Based Materials**: 1 *[medium term]*
    Establish and adapt automotive industry standards for bio-based materials to ensure consistency in quality and performance in comparison to conventional polymers. This may involve collaboration with regulatory bodies and industry stakeholders.

  - **Efficient Recycling Processes**: 2 3 *[short term]*
    Develop recycling processes specifically tailored for innovative bio-based materials, addressing challenges such as biodegradability and contamination with traditional plastics.

  - **Research Regarding Natural Fibers/Textiles**: 1 *[short term]*
    Investigate the potential for using natural fibres and textiles in automotive applications, focusing on their mechanical properties, durability, and environmental impact.

- <u>**PFAS**</u>

  - **Identifying Alternatives**: *[short term]*
    Conduct research to identify and develop alternative substances that can replace PFAS in automotive applications, focusing on maintaining performance while reducing environmental impact.

  - **Redesign Approaches**: *[short term]*
    Implement redesign strategies that minimize or eliminate the use of PFAS in products, including the development of safer chemical formulations.

  - **Long-Term Substitution Measures**: *[long term]*
    Establish long-term research initiatives aimed at achieving total substitution of PFAS in automotive applications following EU regulation to phase out PFAS by 2030, including collaboration with chemical manufacturers and regulatory agencies.

2.2 Circularity Strategies beyond Material Recycling

Circularity strategies are increasingly vital in the automotive industry as they address pressing environmental challenges and resource scarcity. By shifting from traditional linear models of production and consumption to circular practices, automotive companies can reduce waste, enhance resource efficiency, and promote sustainability throughout the vehicle lifecycle. Implementing these strategies not only aligns with regulatory frameworks like the EU Circular Economy Action Plan [6] but also fosters innovation, improves competitiveness, and meets the growing consumer demand for sustainable products. Ultimately, embracing circularity is essential for the industry's transition towards a more sustainable and resilient future.

State of the Art:

In recent years, the concept of circularity has gained significant traction within the automotive and transportation sectors, driven by the urgent need to address environmental challenges and resource scarcity. Circularity strategies aim to create a sustainable system where resources are utilized efficiently, waste is minimized, and products are designed for longevity and reuse. Central to these strategies are frameworks such as the EU Circular Economy Action Plan and the "9R" framework, which provide structured approaches to implementing circular practices.

The EU Circular Economy Action Plan [6], part of the European Green Deal, outlines a comprehensive strategy to transition Europe towards a more sustainable economy. It emphasizes the importance of reducing waste, promoting resource efficiency, and fostering innovation in product design. The plan sets ambitious targets for recycling and waste management, encouraging industries to adopt circular principles that extend the lifecycle of products and materials. By integrating circularity into economic policies, the EU aims to create a resilient economy that not only benefits the environment but also enhances competitiveness and job creation.

Complementing the EU's efforts, the 9R framework [3] offers a detailed roadmap for achieving circularity through nine interconnected strategies: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Recycle, and Recover. Each "R" represents a critical step in the circular economy, guiding organizations in their efforts to minimize waste and maximize resource efficiency. This framework encourages businesses to rethink their operations and product designs, fostering a culture of sustainability that prioritizes the responsible use of materials.

Challenges:

Beyond material recycling, the automotive industry faces several significant challenges in implementing circularity strategies in relation to the EU Circular Economy Action Plan and the 9R framework (Fig. 2). These challenges include:

- **Transitioning Business Models**: Shifting from traditional linear business models to circular ones requires a fundamental change in how companies operate. This includes moving from a focus on sales volume to value creation through services like leasing, car-sharing, and product-as-a-service models as well as (global) systemic modular design of key car components.
- **Design for Longevity and Repairability**: Implementing the principles of the 9R framework necessitates redesigning vehicles and components to enhance longevity, repairability, and

upgradability. This requires collaboration among various stakeholders, including designers, engineers, and suppliers, which can be complex to manage.

- **Consumer Acceptance and Behaviour Change**: Encouraging consumers to adopt circular practices, such as participating in car-sharing or accepting refurbished components, requires significant shifts in consumer attitudes and behaviours. Educating consumers about the benefits of circularity and fostering a culture of sustainability is essential but challenging.
- **Supply Chain Integration**: The automotive supply chain is extensive and often global, making it difficult to implement circular practices consistently across all levels. Ensuring that all suppliers adhere to circularity principles and sustainability standards can be a significant challenge.
- **Regulatory Compliance and Variability**: The EU Circular Economy Action Plan introduces stringent regulations and targets for waste reduction and sustainability. Navigating these regulations, which may vary by region, can be complex and requires careful planning and adaptability.
- **Technological Innovation and Investment**: Developing innovative technologies and processes that support circularity, such as modular vehicle designs or advanced remanufacturing techniques, requires substantial investment in research and development. Securing funding for these initiatives can be a barrier, especially in a competitive market.
- **Cultural Resistance to Change**: Shifting to circularity often necessitates a cultural change within organizations. Employees may resist new practices or processes, making it essential for leadership to foster a culture of sustainability and innovation.
- **Quality Control in Reuse and Remanufacturing**: Ensuring the quality and safety of reused or remanufactured components is critical. Automotive companies must develop rigorous quality control processes to maintain consumer trust and comply with safety regulations.
- **Data Management and Transparency**: Implementing circularity strategies requires accurate data on product lifecycles, usage patterns, and performance metrics. Establishing systems for data sharing and transparency among stakeholders can be complex and may raise concerns about confidentiality and competition.
- **Collaboration Across Sectors**: Achieving circularity often requires collaboration beyond the automotive industry, including partnerships with other sectors, governments, and research institutions. Building and maintaining these collaborative networks can be challenging but is essential for success.

Addressing these challenges is crucial for the automotive industry to effectively implement circularity strategies in alignment with the EU Circular Economy Action Plan and the 9R framework, contributing to a more sustainable and resilient future ultimately.

Research Needs

The most important research needs regarding circularity strategies in the automotive industry on vehicle and system level include:

- **Design for Circularity**: *[short term]*
  Research focused on developing LCA-based methodologies, tools and design principles that

prioritize circularity and the use of sustainable materials enabling the implementation of the 9R framework

- **Business Model Innovation**: ❷❸ *[medium term]*
Exploring new business models that support circularity, such as product-as-a-service, car-sharing, and remanufacturing. Research in this area focuses on understanding how these models can be effectively implemented and scaled within the automotive industry.
- **Consumer Behaviour and Acceptance**: *[short term]*
Investigating consumer attitudes and behaviors towards circular products and services. Understanding what drives consumer acceptance of circularity initiatives is crucial for developing effective marketing strategies and promoting sustainable practices.
- **Supply Chain Management**: ❷❸ *[medium term]*
Researching strategies for managing circular supply chains, including collaboration with suppliers, logistics optimization, and the integration of circularity principles into procurement processes. This area aims to enhance the efficiency and sustainability of the entire supply chain.
- **Regulatory and Policy Frameworks**: ❷ *[medium term]*
Analysing the impact of existing and emerging regulations on circularity in the automotive sector. Research in this area focuses on identifying policy gaps and proposing frameworks that encourage circular practices while ensuring compliance.
- **Collaboration and Stakeholder Engagement**: ❸ *[short – medium term]*
Exploring effective strategies for fostering collaboration among various stakeholders, including manufacturers, suppliers, consumers, and recycling facilities. Research in this area aims to identify best practices for building partnerships that support circularity.
- **Impact Measurement and Reporting**: *[short term]*
Developing metrics and frameworks for measuring the effectiveness of circularity strategies. This includes establishing key performance indicators (KPIs) that can help organizations track progress and communicate their sustainability efforts.

By focusing on these research areas, the automotive industry can advance its understanding and implementation of circularity strategies, contributing to a more sustainable and resilient economy ultimately.

2.3 Role of Digitalisation

In the pursuit of a sustainable future, the automotive industry is increasingly recognising the importance of digitalisation in fostering a Circular Economy. This chapter discusses several focus topics that are essential for integrating digital solutions into the automotive value chain, thereby enhancing circularity, sustainability and efficiency.

<u>State of the Art</u>:

The automotive industry is transitioning towards a more sustainable and resource-efficient future, with digital technologies playing a critical role in enabling circular economy strategies. By leveraging data-driven solutions, manufacturers, suppliers, and recyclers are improving traceability, reuse, and material recovery across the entire vehicle lifecycle. Innovations such as Digital Product Passports, AI-assisted analytics, and digitally enhanced sorting technologies are transforming how automotive components and materials are managed, ensuring they remain in circulation for as long as possible. Besides, the new Ecodesign for Sustainable Products Regulation (ESPR) by the European Union [14] specifically demands digital solutions supporting sustainability and resource-efficiency.

A significant challenge in the circular economy is locating and retrieving end-of-life vehicles (ELVs) and components that can be reused or recycled. Digital tracking technologies, including IoT sensors, blockchain-based registries, and RFID tagging, are increasingly being deployed already to monitor vehicle parts throughout their lifecycle. These solutions improve transparency and enable more efficient recovery processes. RFID and QR-based tagging allow for real-time tracking of high-value components such as batteries, electronics, and structural materials, ensuring they are reintegrated efficiently into supply chains instead of being lost or discarded.

To facilitate reuse, repair, and recycling, Digital Product Passports (DPPs) are being introduced to store detailed information on the composition, repair history, and environmental footprint of automotive components. These digital records help streamline circular strategies by ensuring that every part carries essential data for disassembly, remanufacturing, or recycling.

Similarly, Battery Passports [15] are being developed to track key parameters of electric vehicle batteries, including their chemistry, state-of-health, usage history, and potential for second-life applications. These passports enable better lifecycle management, allowing used batteries to be repurposed for stationary energy storage or safely processed for material recovery. Regulatory frameworks [7] are increasingly promoting the adoption of such digital passports to enhance transparency and ensure responsible resource utilization.

Online platforms are emerging as a key enabler of component reuse and material circulation. Digital marketplaces connect manufacturers, service providers, and recyclers, allowing for the efficient exchange of used or refurbished components. By leveraging AI-driven pricing algorithms and demand forecasting, these platforms optimize the valuation and availability of used parts, making reuse a more attractive and economically viable option.

Artificial intelligence is becoming an essential tool in assessing the usability of components and materials. AI-assisted state-of-health analytics enable precise evaluation of parts, particularly batteries and powertrains, determining their remaining lifespan and optimal reuse scenarios. Predictive maintenance and degradation analysis help extend the life of components, ensuring that they are repurposed or recycled at the right time. Machine learning models enhance decision-making by identifying the best pathways for refurbishment, reuse, or material recovery.

Efficient material sorting is a key factor in maximizing recycling rates and ensuring high-quality secondary raw materials. Advances in digitally enhanced sorting technologies, such as hyperspectral imaging, AI-driven robotics, and automated classification systems, are improving the separation of metals, plastics, and composite materials from end-of-life vehicles. These technologies enable recyclers to extract valuable resources more efficiently, minimizing contamination and ensuring that recovered materials meet industry standards for reuse.

The integration of digital twins is enhancing lifecycle management by creating virtual models of vehicles and components. These digital representations track real-time data throughout the lifecycle, from production to end-of-life, enabling predictive maintenance, optimized disassembly, and material recovery planning. By leveraging digital twins, manufacturers and recyclers can design products with circularity in mind, improving material efficiency and reducing waste.

Challenges:

The automotive industry's transition to a circular economy relies on digital technologies like IoT, blockchain, AI, and digital product passports to improve tracking, reuse, and recycling of materials. However, several challenges impede progress:

- **Lack of Standardised Data and Interoperability:** Different stakeholders in the supply chain use varying data formats and tracking systems, making data exchange difficult. The absence of universal standards for Digital Product Passports and inconsistent labelling methods hinders automated sorting and material recovery.
- **Track and trace:** Further activities are needed in alignment with the existing EU approaches, e. g. Catena-X or the Digital Battery-Passport to enhance digital tracking of supply chains, components and vehicles along their lifecycle. In addition, physical tracking with the help of markers is also desirable to secure the data or to provide data for the digital level through scanning processes (e.g. law-fulfilling effect or added value for companies to be able to replace audits).
- **Limited Adoption of Digital Twins, Digital Product and Battery Passports:** The adoption of Digital Twins, Digital Product Passports, and Battery Passports is slow due to fragmented supply chains, regional regulatory differences, and challenges around secure, accessible data storage and exchange.
- **High Costs and Investment Requirements:** Implementing advanced technologies requires significant investment, which many smaller suppliers and recyclers cannot afford. The delayed ROI from such technologies also slows down adoption.
- **Data Privacy and Cybersecurity Risks:** Tracking sensitive component data raises concerns about data privacy and cybersecurity, with the need to comply with regulations like GDPR adding complexity to cross-border data sharing.
- **Incomplete Digital Infrastructure for Recycling and Remanufacturing:** Many recycling facilities still rely on outdated processes, limiting the use of AI and real-time tracking for optimizing recycling and remanufacturing.
- **Complexity of Multi-Stakeholder Collaboration:** Achieving end-to-end lifecycle tracking requires collaboration among stakeholders with different digital capabilities, business models, and regional regulations, making coordination challenging.
- **Regulatory and Legal Uncertainties with regional dependencies:** Evolving regulations on extended producer responsibility (EPR), digital passports, and sustainability create uncertainty,

complicating the implementation of consistent long-term strategies. Furthermore, legal or organizational aspects are a major hurdle to the implementation of physical tracking methods.

For a successful circular economy in the automotive sector, challenges like data standardization, investment, cybersecurity, and regulatory alignment must be addressed. Collaboration, digital infrastructure investment, and regulatory clarity will be key to overcoming these obstacles and achieving sustainability goals.

Research Needs:

To enable a fully digitized circular economy in the automotive industry, several critical areas require focused research and development:

- **Standardisation of Data Formats and Protocols**: ❷❸ *[short term]*
  Research is needed to establish universal standards for data formats, digital product passports, and tracking systems. Standardisation will improve interoperability across different platforms and stakeholders, facilitating smoother data exchange and automating the tracking of materials and components throughout their lifecycle.
- **Advanced AI and Machine Learning for Component Health Monitoring:** *[short term]*
  There is a need for enhanced AI-driven solutions to assess the health and remaining life of automotive components, particularly batteries and high-value parts. Research into more accurate, real-time health monitoring and predictive maintenance models will be crucial for enabling more effective reuse and remanufacturing of parts.
- **Blockchain and Distributed Ledger Technologies**: ❷❸ *[long term]*
  Research into improving the scalability, security, and efficiency of blockchain and distributed ledger technologies for tracking automotive parts and materials is essential. These technologies can provide tamper-proof records of a part's lifecycle, enabling greater transparency and accountability in the circular economy.
- **Digital Product Passports and Battery Passports:** ❷❸ *[short term]*
  Developing more detailed, standardized and interoperable Digital Product Passports and Battery Passport solutions is a critical research area. These passports should capture key data such as component health, material composition, recyclability potential, and repair history to improve tracking and facilitate the reuse and recycling of automotive components. On this basis automated data analysis of DPP data and decision support systems should be developed to optimize product and process design parameters with regard to their circularity (easy to dismantle, easy to recycle).
- **Digital Tracking and Tracing Technologies of Vehicles:** ❷❸ *[short term]*
  Research is needed to track and trace vehicles until they reach end-of-life status regardless of their age and location as well as the reusable components and recyclable materials including the certified data exchange of relevant circular KPIs. This is important to bring unknown-whereabouts in organization and legally compliant dismantling and recycling system.
- **AI-Assisted Dismantling, Sorting and Recycling Technologies:** ❷❸ *[short term]*
  Research is needed to enhance the capabilities of AI-driven systems for dismantling, sorting and recycling materials in automotive manufacturing. Improved image recognition, robotic dismantling

and sorting. Parts and material classification methods can help automate and optimize dismantling and recycling processes, improving the efficiency and quality of recovered parts and materials.

- **Data Privacy and Cybersecurity in Circular Economy Models:** *[short term]*
  With the increase in digital tracking and sharing of data, particularly for sensitive component information, research into secure, privacy-compliant data management practices is necessary. This includes developing encryption methods, decentralized data storage systems, and secure data-sharing protocols to protect intellectual property and comply with privacy regulations.
- **Integration of Circular Economy into Digital Supply Chain Management:** ❷❸ *[short term]*
  Research should focus on the integration of circular economy principles into digital supply chain systems while complying with GDPR. This involves developing platforms that enable real-time tracking, forecasting, and decision making to optimise the flow of materials and components while minimizing waster.
- **Regulatory and Policy Impact Studies:** *[short term]*
  To support the adoption of digital circular strategies, research on the regulatory frameworks governing data management, recycling (and overall R-strategies), and extended producer responsibility (EPR) is essential. Understanding the impact of evolving regulations on the automotive sector's digital transformation will help businesses navigate legal challenges and ensure compliance.
- **Economic and Environmental Impact Models:** *[long term]*
  Research should also focus on modelling the economic and environmental impacts of a digitized circular automotive industry. By developing predictive models, stakeholders can better understand the potential benefits and challenges, including cost savings, resource efficiency, and reductions in carbon emissions, resulting from digital circular strategies.

Advancing digitization in a circular automotive industry requires interdisciplinary research in data standardization, AI, blockchain, privacy, and regulatory frameworks. Addressing these research needs will help create a more efficient, transparent, and sustainable automotive ecosystem.

2.4 Components and Assemblies

The automotive industry is increasingly embracing circular economy principles to reduce waste, conserve resources, and enhance sustainability. This shift is driven by the need to create a more sustainable future while addressing the environmental impacts of vehicle production and end-of-life management. New product development is already very complex since OEMs and their Tier 1 suppliers have to include different aspects (Design to X, low production costs, high quality level etc…) and make some compromises. Adding Design for Circularity to increase product lifetime and to save natural resources and emissions will add another layer of constraints which will increase complexity

State of the Art:

Here are the key strategies currently in place for automotive components and assemblies:

- **Production Focus:** Today, most the attention in the design process is put on durability, easy production/assembly and to some extent modularity. Little to no attention is given to design for disassembly as per linear business rational that companies operate in.
- **Modular Design**: Existing applications of modular design focus on reducing part numbers while maximizing product variants. These efforts aim at increasing cost-efficiency in the upstream flow but leave the mid/end-of-life handling neglected. Modular principles such as standardized interfaces over time are not connected to disassembly or recovery at end-of-life.
- **Remanufacturing**[4]: While remanufacturing practices exist today, they are operated on a small scale as niche business. In Europe the reman intensity has been estimated with 1,9% (ratio of remanufactured to new manufacturing). For the Automotive industry this is even lower with an intensity of 1,1% [16]. Key components of engine and transmission systems such as electric motors, clutches, axles, shock absorbers, in addition to steering and chassis parts & assemblies are being currently remanufactured, reducing the need for new parts and preserving valuable materials.

Increasing the reuse of automotive components is another key element of circularity:

- **Battery Second-Life Applications**: Used electric vehicle (EV) batteries are being repurposed for energy storage applications, providing value before eventual recycling. While these repurpose activities are not yet operated at scale, they are expected to increase once more EVs reach their end-of-life. Some modules can be also reused to reman/repair battery packs for automotive.
- Spare **Parts Reuse**: Components like airbags, electronics, and glass can be refurbished and reused, reducing the need for new parts.

Remanufacturing is a significant strategy for extending the lifecycle of automotive components. Many high-value parts, such as engines and transmissions, can be restored to their original specifications through remanufacturing, which involves the Refurbishing, Repair, Exchange, Upgradation, and/or Reuse of individual Parts and Components.: Parts such as power steering pumps and brake callipers are refurbished to extend their use in order to reduce material waste and environmental impact.

The automotive industry’s circularity strategies focus on design for disassembly, remanufacturing, reuse of components, and material recovery through recycling. These strategies are vital for reducing waste, conserving resources, and minimizing environmental impact. Continued innovation in eco-design, sustainable materials (e.g. bio-sourced or recycled), and efficient manufacturing processes is essential for advancing the circular economy in automotive production.

As the industry moves forward, initiatives like the 2Zero Partnerships' ZEvRA project [17] and the French national project DECORE [18] are paving the way for improved circularity across the entire value chain. By addressing both upstream and downstream ecosystems, the automotive sector can enhance competitiveness, lower raw material dependency, and reduce costs through efficient reuse and remanufacturing of components. However, the current business landscape reveals challenges in existing supply chains and value networks, necessitating initiatives like ReCiPSS to implement circular

[4] Remanufacturing is the process of bringing used or broken parts and components to the same specifications as new components or better (through upgrades). A remanufacturing process includes the following steps: inspection, disassembly, part replacement/refurbishment, cleaning, reassembly, and testing to ensure it meets the desired product standards/quality. Remanufactured components have the same quality as warranty as new parts. There are other practices like refurbishment and reconditioning, however, these have different (often lower) quality requirements and are therefore priced lower.

manufacturing systems. Ultimately, the integration of Lifecycle Assessment (LCA) methodologies will be crucial in evaluating the environmental impact of these approaches, ensuring a sustainable future for the automotive industry.

Challenges:

As the automotive industry strives to adopt circularity principles for components and assemblies, several key challenges in view of the transition towards zero-emission vehicles remain that need to be addressed:

- **Design for Disassembly and Reuse:** Many automotive components are not designed with easy disassembly in mind, making it difficult to recover and reuse parts. Complex assemblies such as electrified drivetrain, battery systems or those from the E&E domain that use mixed materials (metals, plastics, composites) can be especially challenging to separate effectively for reuse or recycling.
- **Efficient Remanufacturing Processes:** Many automotive components and assemblies, such as (electric) engines, transmissions, and electronic components, can be remanufactured but require precise assessment of their condition especially in terms of ageing, wear & tear that individual parts undergo during their use. The remanufacturing process often involves time-consuming and costly inspections, repairs, and testing. Such assessments related to evaluating the Ageing and Fatigue in parts along with the prediction of their failure modes with further use is still lacking.
- **Quality and Safety Standards for Reused, Repaired and Refurbished Components:** Ensuring the quality, safety, and performance of Reused, Repaired and Refurbished components is a significant challenge. Standardized testing and certification procedures to ensure that Reused, Repaired, Refurbished components meet industry standards, in a way similar to associated warranties provided for Remanufactured parts to the consumer is still lacking.
- **Consumer Acceptance and Market Demand:** There is still resistance from both consumers and manufacturers regarding the use of reused or remanufactured components or assemblies, largely due to perceptions of lower quality or safety concerns.
- **Maximizing vehicle lifetime** and enabling its upgradability over its entire use phase including multiple life cycles is a key topic for manufacturers to increase attractiveness, vehicle lifetime & residual value and at the same time avoid obsolescence. Upgradability of different vehicle systems such as On-Board EEEDS systems (including Head-up Displays, Instrument panels, ADAS systems etc.) is particularly lacking even over a single Use life.

To overcome the challenges of circularity in automotive components and assemblies will play a critical role to manage the transformation from a linear to a circular economy.

Research Needs

Addressing these challenges of circularity is crucial for transitioning to a more sustainable model. The most important research needs related to the challenges regarding components and assemblies are:

- **Design for Disassembly and Reuse:** *[medium-term]*
  Development of modular, reconfigurable and standardized designs that facilitate easy disassembly and reassembly of components in combination with new fastening methods and reversible bonding

alternatives to adhesives that allow for easy disassembly without compromising the integrity of the components during their lifecycle.

- **Efficient Remanufacturing Processes:** ❷❸ *[medium-term]*
  Development of advanced diagnostic tools and technologies (e.g., AI and machine learning) for real-time assessment of component conditions to streamline the remanufacturing process. This should be completed through research on the optimization of remanufacturing processes, including automation and robotics, to reduce time and costs associated with inspections and repairs. There is a specific focus to be made on components/modules: ADAS, E-Motors, Power Electronics, Batteries.

- **Quality and Safety Standards for Reused, Repaired and Refurbished Components:**
  ❷❸ *[medium term]*
  Development standardized testing and certification protocols for reused and refurbished components to ensure they meet safety and performance standards. This should be completed by an investigation to create a regulatory framework that supports the certification of Reused, Repaired and Refurbished components, ensuring compliance with industry standards. Hence, development and definition of tests and certification to assess the quality and reliability of such components considering ageing mechanisms in parts and materials through wear & tear, under different use conditions would be necessary.

- **Consumer Acceptance and Market Demand:** *[short term]*
  Perform comprehensive market research to understand consumer attitudes towards reused and remanufactured components, identifying barriers to acceptance. In particular, the safety perceptions of consumers regarding reused components and develop strategies to address these concerns must be addressed. This should be complemented by research on effective communication strategies and campaigns that can educate consumers about the benefits and safety of remanufactured products. Finally, the development of incentive programs for consumers and manufacturers to encourage the adoption of reused and remanufactured components should be included.

- **Vehicle Upgradability –** *[short - medium term]*
  E&E systems architecture and software system upgradability:
  There is specific research need on allowing/realizing upgradeability of the EDS/EEEDS systems over single and multiple lives. This is important to maintain customer acceptance and the ease of use of the vehicle with up-to-date technical features related to ADAS, vehicle software upgrades associated with autonomous driving etc.

- **System level and standardized LCA** *[long term]*
  considering Reverse Flows covering multiple life cycles would to assess the carbon footprint efficiencies and residual value maximization of parts & assemblies associated with the implementation of circular strategies like Remanufacturing, Refurbishing and Recycling.

Addressing these research needs will be essential for overcoming the challenges of circularity regarding components and assemblies. By focusing on design, remanufacturing processes, quality standards, and consumer acceptance, the industry can make significant strides towards a more sustainable and circular economy.

2.5 Charging and Road Infrastructure

The final element in achieving a circular road transport sector is the infrastructural assets that form our road transport network.

State of the Art

The construction sector is responsible for about 50% of extracted materials globally, with significant associated emissions. A 2023 report[5] by the European International Contractors (EIC), European Construction Industry Federation (FIEC) and European Network of Construction Companies for Research and Development (ENCORD) concluded that:

"Up to 90% of primary resources will need to be reused to achieve carbon and resource neutrality by 2050 which will require radical change across the entire construction ecosystem. A systems thinking approach is needed across the construction ecosystem."

The report, endorsed by Commissioner Maroš Šefčovič, advocates a shift from a linear to a circular business model, and indicates the scale of change that is required for managing road infrastructure assets. In this context, there is a clear need for more efficient use of materials. When assessing the materials used in our infrastructure, asphalt has very high reuse rates (70-75% is currently reused as asphalt) but this is still below the required targets. There is scope for further improvement through the use of novel materials (e.g. bio-binders) and this remains a technical challenge. The requirements for other assets (e.g. concrete elements or charging infrastructure) are less clear. Circular economy principles require that materials should be re-used at their highest value, necessitating a complete change in how these assets are managed. Demolition will be replaced by deconstruction, but the subsequent reuse of these assets will also bring several additional challenges relating to variability, certification, performance, regulation etc.

The underpinning technologies that will help deliver a circular road infrastructure are digital, and the need for digitally connected data that fully integrates the road transport ecosystem. Significant advances have been made in addressing discrete technical challenges, but there are still major knowledge gaps on how the data is integrated and how it can be best used to deliver the required paradigm shift.

Challenges

The challenges for implementing the circular economy in managing road infrastructure assets are myriad and include:

- **Public procurement:** Much of our transport infrastructure is built using public funds, with strict contractual rules. How do we allow for the uncertainty that can go with the use of circular materials? Furthermore, the benefits arising from a circular approach may not be seen for years / decades; how do we measure and recognise these benefits?

- **Digital inventory:** A clear understanding of the existing infrastructure is essential if circularity is to be achieved; however much of this infrastructure is already in place, and some of it for a very long time. These assets may be a source of significant uncertainty, and the absence of detailed digital

[5] https://www.fiec.eu/application/files/8317/0290/2290/FIEC_EIC_ENCORD_Joint_vision_on_achieving_carbon_and_resource_neutrality.pdf

information on what the infrastructural elements actually are, is a major barrier to their re-use. This also links to **Digital Product Passports** and **Environmental Product Declarations**; these will soon become the norm for new construction, but is this compatible with the circular economy?

- **Market place**: Infrastructural elements can be reused across transport modes (e.g. an old railway bridge can be re-purposed as a pedestrian bridge over a road). It may also be possible for charging infrastructure to be reused in other contexts. However, these projects require time / space, and there are significant logistical and coordination challenges. Facilitating these transactions across countries/modes will be a major challenge and will present new and unexpected supply chain difficulties.

- **Regulatory challenges** also persist across the EU and create a barrier to the circular economy. These are frequently risk-averse and inflexible, and act as a significant impediment. In this environment there is no incentive for those seeking to adopt circular principles, and the absence of policy support for CE is often pointed to. A related principle is financial – the benefits for CE are often not realised in the short term. The absence of business models that support long-term financing is an additional challenge.

- **Life cycle management:** Traditional approaches to infrastructure management remain linear – there is a progression from design to construction to operation/maintenance and then end of life. There is a clear boundary between each step, and frequently this involves a new company taking leadership at each step. This linear approach is not compatible with circularity, and new business models are required that will remove fragmentation issues and instead promote life cycle approaches.

Research needs

Responding to these challenges, the following research needs are identified:

Public Procurement as an Enabler of Circular Economy

- **Flexible Procurement Frameworks for Circularity:** [*short term*]
  Research is needed to develop public procurement models that promote circularity for infrastructure assets, while addressing uncertainties related to quality, uncertainty, and long-term performance.

- **Economic and Environmental Impact Assessment of Circularity:** [*medium term*]
  New methodologies are needed for quantifying the long-term benefits of circular economy practices in transport infrastructure. These can include life-cycle costing, socio-economic benefits and support of sustainable development goals.

Digital Infrastructure Data Assessment

- **Digital Inventories of Existing Infrastructure:** [*short-medium term*]
  Digitalisation is the key enabler of circular economy, but there is a severe lack of digital data for existing infrastructure assets. This should be addressed through inspection programmes, through tools such as AI, remote sensing, machine learning for material identification and structural assessment.

- **Integration of Digital Product Passports and Circular Economy:** [*short-medium term*]
  Digital Product Passports (DPPs) and Environmental Product Declarations (EPDs) are emerging as critical tools for delivering infrastructure more sustainably. Methodologies are needed for integrating these new processes with existing infrastructure assets.

Marketplace for Reused Infrastructure Components

- **A Digital Marketplace for Circular Infrastructure:** [*long term*]
  Circular economy allows existing infrastructural assets to be used across modes and in contexts quite different to what they were originally designed for. Maintaining information on the assets will be essential there is a need for digital platforms or blockchain-based systems that facilitate the trading, tracking, and certification of infrastructural components across transport modes.

- **Optimizing Logistics for Circular Infrastructure:** [*long term*]
  As the circular economy of infrastructural assets is established, an increasing number of elements will become available. These are likely to be large, heavy and cumbersome and the storage / management of these will present severe logistical challenges. A coordinated approach for storage and transportation for assets across Europe will be needed.

Regulatory and Financial Challenges

- **Harmonizing Circular Economy Regulations:** [*long term*]
  A detailed assessment of the regulatory barriers that impede circular economy is needed, along with policy recommendations for best practice that can promote standardisation across member states.

- **New Business Models for Long-Term Circular Investments:** [*long term*]
  The benefits of circular economy are often not realised in the short term, and current financial methodologies do not recognise this. There is a need for new business models that promote circularity and recognise that delayed financial returns may need to be accommodated.

Life Cycle Management and Business Models

- **Developing Circular Lifecycle Management Strategies:** [*medium term*]
  Identifying mechanisms to integrate circular economy considerations at each stage of the infrastructure life cycle, so as to ensure that design, construction, operation, and maintenance facilitate reuse and repurposing. This is particularly needed for charging infrastructure, given the current strong emphasis on deployment.

- **Life Cycle Analysis into Circular Infrastructure Decision-Making:** [*medium term*]
  There is a need for LCA-based frameworks that assess the environmental and economic impacts of circular infrastructure practices across all life cycle stages, ensuring that all proposed strategies provide measurable benefits.

3 Conclusions and Recommendations

To meet the challenging requirements of the ELV Directive proposal, ERTRAC suggests several comprehensive research programs and projects aimed at providing the techno-economic foundation for the upcoming transformation through collaborative R&D. As this transformation is expected to take several decades, with entirely new technologies - such as artificial intelligence, robot-based dismantling, cradle-to-grave traceability of vehicles, components, and raw materials, and new material sorting technologies - needing to be developed, industrialized, and scaled, significant efforts, resources, and investments from all stakeholders will be required to increase circularity significantly. Therefore, ERTRAC suggests a two-layer approach for future collaborative R&D programs:

Firstly, it proposes three large-scale, industry-led lighthouse projects on European level. that should be managed in a similar way such as the Road-and-Belt Initiative (China), the Lightspeed (USA), and Stargate (USA) projects with continuous attention and support at the highest possible level with ample funding supported by the best available project management practices and capable human resources.

The rationale for focusing efforts on these projects is straightforward: only by deploying substantial private and public resources in the multibillion-euro range the EU will be able to leapfrog circularity and competitiveness to the next level in a timely manner. These projects should be integrated into the Next Framework Programme ("FP10") and other frameworks. They could provide the foundation for a fifth industrial revolution and a new economic boom within the EU and globally [19]. The success of these lighthouse projects requires intensive collaboration between various industries, scientific institutions, NGOs, the banking/private equity/venture capital industries, and governments at both national and EU levels. Additionally, a new organizational framework will be needed to manage them at high speed while staying globally competitive. Moreover, tight monitoring must make sure that these projects contribute to the EU Green and Clean Industrial Deal targets and further economic growth of the European Union. The success of these lighthouses is strongly dependent on specific laws, regulations, incentives and the implementation of advanced change management practices to make sure that all involved stakeholders will perceive them as beneficial.

Secondly, these large projects should be complemented by smaller initiatives and projects on national and/or European levels that focus on specific research and innovation needs but are highly interconnected with the three light house projects. They should start as soon as possible embedded in existing or future national and/or European public, academic and corporate research and innovation frameworks. These smaller R&I initiatives and projects will advance key technologies, innovations, and business models, supporting the three lighthouse projects as well as other identified challenges in the area of vehicle circularity.

However, the transition to a circular economy requires a fundamental shift in industries, infrastructure and consumer behaviour. Besides investments in R&D and infrastructure as described in this roadmap and legislative efforts, a consistent and structured change management on large scale must be implemented integrating all stakeholders (from policy and legislation, business, research and public). Only if all stakeholders together co-design this change taking up lessons learned, a smooth transition towards a more circular economy can be achieved. Being the first succeeding with the required transition, the EU will be world-leader for a sustainable and efficient economic system that benefits businesses, consumers, and the environment alike.

3.1 Light House Projects

The three proposed lighthouse projects focus on the most significant challenges to improve automotive circularity. The significantly rising automotive polymer demand, the high percentage of unknown whereabouts and the high fragmentation of the recycling industry (Fig. 5). For all three projects preparation of R&I activities have already started to set up large scale European transformation projects (Fig. 6):

- The defossilisation of automotive polymers to reach carbon neutrality by 2050,
- The integration of unknown whereabouts into a future transcontinental end of live vehicle recycling system and
- The establishment of large industrial pan-European recycling industry champions that are able to develop, implement and scale semiautomated or automated vehicle disassembly and the production of automotive grade secondary materials at low cost.

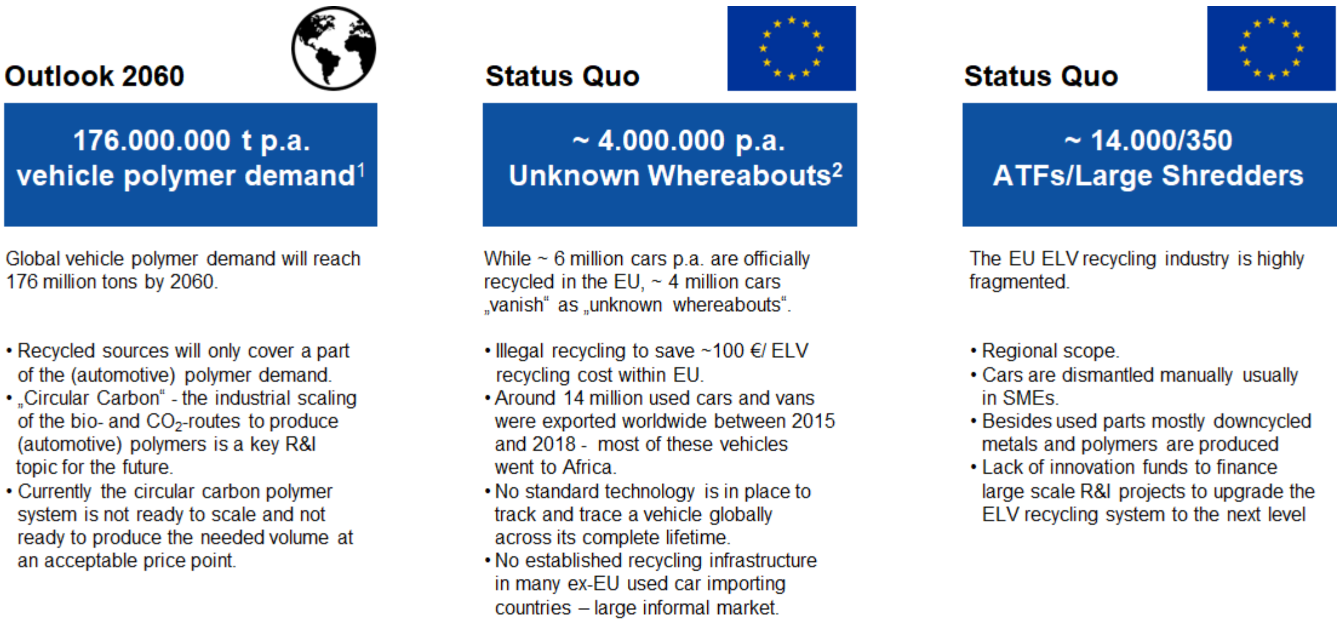

Figure 6: Major Circular Economy Challenges in the Road Transport Sector [20][6]

[6] Source: OECD Global Plastics Outlook: Policy Scenarios Until 2060, Figure 3.4, Baseline Scenario
Source: Umweltbundesamt: Effectively tackling the issue of millions of unknown whereabouts, Scientific opinion paper 2020,
Source: https://ec.europa.eu/environment/pdf/waste/elv/ELVD%20Evaluation-Final%20report%20Aug2020-rev1.pdf, p.4

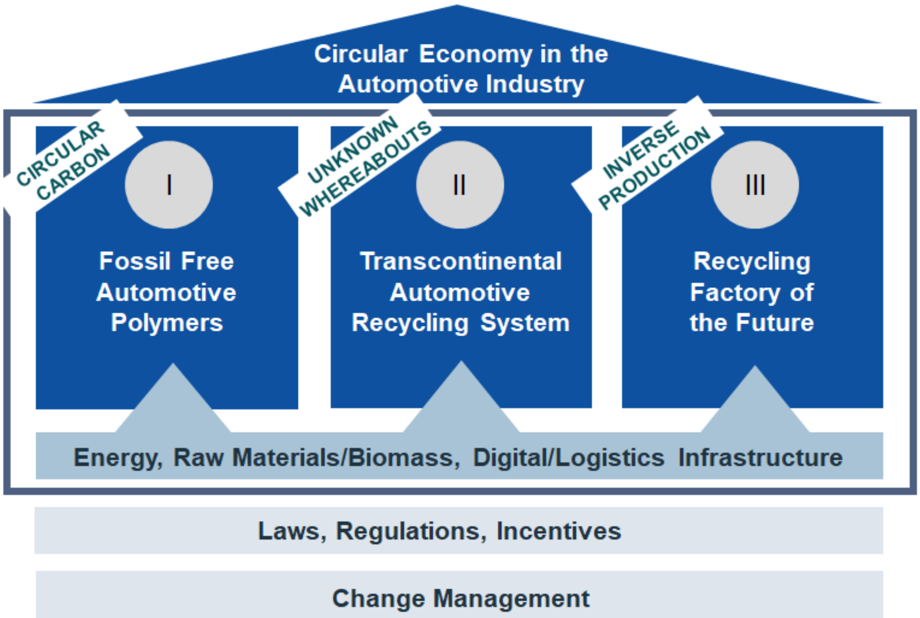

Figure 7: Proposed Circular Economy Lighthouse Projects [21]

3.1.1 Fossil Free Automotive Polymers

The challenge of reducing the CO_2 footprint of polymers to “Net Zero” by 2050 is immense. There are three main routes to achieving this: polymer recycling, biobased polymers, and CO_2-based polymers. Currently, the transition to fossil-free automotive polymers is in its early stages and must be accelerated significantly to meet increasingly stringent open and closed-loop secondary raw material quotas for automotive polymers and finally a “Net Zero” carbon footprint.

To reach these targets, advancements in polymer sorting technologies, as well as mechanical and chemical recycling routes for high-performance polymers used in the automotive industry, must be developed and implemented rapidly. The automotive polymer market is expected to continue growing until 2050 and beyond, making this transformation even more critical.

However, even under optimal conditions, polymer recycling alone will not be able to meet the full global and automotive demand for polymers. Therefore, the production of biobased feedstock for bio-naphtha or other base chemicals, combined with the capture of CO_2 from point sources or ambient air, will be essential. Additionally, the large-scale production of green or turquoise hydrogen will be crucial in driving the forthcoming global transformation to fossil-free polymers.

New technologies, such as microalgae farming and direct air capture, will be crucial in achieving carbon neutrality by 2050. Given the early stage of these emerging industries, their further development must be accelerated significantly to ensure the timely achievement of sustainability goals.

3.1.2 Development of a transcontinental recycling system

Integrating the estimated 40% of decommissioned cars whose whereabouts are currently unknown into a future automotive recycling system will be crucial in advancing automotive circularity to the next level. A significant portion of these decommissioned vehicles is exported to non-EU countries, particularly in Africa, where they provide vital transportation and serve as an important economic resource.

However, the current system creates significant local environmental and road safety challenges in these regions. Many end-of-life vehicles (ELVs) are not properly recycled or adequately maintained and are often operated for as long as possible in suboptimal conditions. As a result, the majority of the materials in these exported vehicles are lost as secondary material sources, making it increasingly difficult to meet certain secondary material targets — both open and closed-loop — within the EU.

To address this issue and take extended producer responsibility seriously, research and innovation (R&I) efforts should focus on the development of local recycling infrastructures and business models tailored to the specific conditions of these regions. By establishing functioning, localized recycling systems, it would be possible to ensure the proper processing of these vehicles, extract valuable secondary materials, and provide these resources back to the international automotive supply chain. Additionally, such initiatives could create new jobs, improve local economic conditions, and minimize environmental hazards, contributing to both global sustainability and regional development.

3.1.3 Recycling factory of the future

The current proposal for regulations on circularity requirements for vehicle design and end-of-life vehicle management mandates the extended dismantling of nineteen different components (Annex VII, Part C). Given that the current dismantling system is primarily reliant on manual labour, it is anticipated that disassembly costs will increase significantly, potentially leading to the collapse of existing business models. To address this challenge, it will be essential to introduce semi-automated or fully automated dismantling processes.

This shift will require the development, industrialization, and scaling of large automotive dismantling and End-of-Life plants capable of processing tens of thousands of end-of-life-vehicles at very low cost. Such an industrial EoL system must be flexible enough to handle various car brands, models, and conditions. It would need to leverage advancements in autonomous reverse logistics, robotics, artificial intelligence, and precision sorting technologies.

One potential approach is to establish a "Recycling Factory of the Future" as a lighthouse project. This initiative could be positioned as an inverse production system, serving as a model not only for the automotive industry but for other sectors as well. It would aim to demonstrate how cutting-edge technologies and new business models can drive circularity at scale.

To ensure the success of such projects, it is critical that new business models, alongside long-term legal and organizational frameworks, are developed and implemented at both the EU and national levels. This will help ensure that the transformation is driven by economic incentives and accelerates at a rapid pace. By doing so, the EU could create a new value-adding industry, driving the next level of automotive circularity and establishing a global leadership position in sustainable automotive EoL approaches (e.g. reuse, 2nd life, remanufacturing, recycling, etc.).

3.2 Limits of a Circular Economy

One has to admit that a circular economy has its physical limits, and a perfect circular economy is not achievable. Any material recovery or recycling process is associated with material losses in varying degrees and additional emissions as well (chemical recycling with high energy demand as one example). These losses must be compensated through primary materials coming from non-fossil sources. Additionally, as global population, and GDP per capita continue to rise and new technologies, products and services will emerge, the demand for new primary materials (and consequently also for secondary materials) will increase. Consequently, Europe must strive for decoupling economic growth from the resource demand and increasing the resource productivity to increase its competitiveness. However, self-sustaining and economic viable business models requires continuous monitoring of material flows (within and outside of Europe) which would result in enormous costs for control and oversight. In times of volatile geo-political constraints, the monitoring and control of material flows (e. g. reverse logistics) may even be not possible. Therefore, both linear and circular economy must be better integrated and managed in a “hybrid” economy model than they are today, while the percentage of the circular economy increases continuously at a high rate.

3.3 Legal Frameworks, Harmonized Roadmaps and Incentives

As with other transformation processes toward a sustainable future, legal frameworks, incentives, and harmonized standards play a crucial role in facilitating the introduction and rapid scaling of research and innovation (R&I) results to establish a circular economy within the EU. For instance, between the early stages of designing a new product line architecture and its eventual end-of-life treatment, a period of two to three decades may pass. This makes it challenging for individual Original Equipment Manufacturers (OEMs) to determine how products should be designed for dismantling by eventually humanoid robots in 2050, which do not currently exist. Without a coordinated approach from both industry and policymakers, or a European Technology Transformation Roadmap extending to 2050 and beyond, there is a significant risk of making highly costly, yet misguided, investment decisions. Therefore, it is highly recommended that a long-term technology and innovation roadmap should be developed in collaboration with various stakeholders, based on systematic R&I, and regularly reviewed, updated and communicated.

The systematic and coherent pricing of negative externalities, such as carbon emissions and other impact categories, will play a pivotal role in shaping investment decisions within the private sector. In this context, it would be highly beneficial to establish a jointly developed long-term scenario extending to 2050 and beyond, which outlines how these prices may evolve over time. A clear and predictable pricing framework can guide businesses and investors in their decision-making processes, enabling them to align with climate goals.

Drawing from past experiences, such as the introduction of electric vehicles and solar energy, government incentives at both the national and European levels can accelerate this transformation significantly. However, based on the lessons learned, it is crucial that these incentives are structured in a way that ensures value creation remains within the European Union and would mitigate risks associated with the forthcoming transformation. This will not only support the EU's climate and economic objectives but also enhance its global competitiveness in emerging green technologies.

4 Annex

4.1 List of Abbreviations

Abbreviation	Meaning
ABS	Acrylonitrile Butadiene Styrene
ABS-PC	ABS - Polycarbonate
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
CARB	California Air Resource Board
CCU	Carbon Capture and Utilisation
CE	Circular Economy
CRM	Critical Raw Materials
DAC	Direct Air Capturing
DMC	Domestic Material Consumption
DPP	Digital Product Pass
EEEDS	European Electrical and Electronic Directives
EoL	End-of-Live
EPR	Extended Product Responsibility
ESPR	Ecodesign for Sustainable Products Regulation
ELV	End-of-Live Vehicle
EV	Electric Vehicle
GAIA-X	initiative to develop a federated secure data infrastructure for Europe
GDP	Gross Domestic Product
ICE	Internal Combustion Engine
LCA	Life-Cycle Assessment
NGO	Non-Governmental Organisation
OEF	Organisation Environmental Footprint
PFAS	Perfluoroalkyl and Polyfluoroalkyl Substances
PEF	Product Environmental Footprint
PLM	Product Lifecycle Management
PP	Polypropylene
PUR	Polyurethane
REE	Rare Earth Element
TCO	Total Cost of Ownership
TPE	Thermoplastic Elastomers
TPV	Thermoplastic Vulcanizates
US	United States
ZEV	Zero Emission Vehicle

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