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DOI
10.1016/j.resconrec.2025.108216

Publication date
2025

Document Version
Final published version

Published in
Resources, Conservation and Recycling

Resources, Conservation & Recycling 218 (2025) 108216

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Increasing plastic circularity in the automotive sector: Supply chain analysis and policy options from the European Union (EU)

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ARTICLE INFO

Keywords:
Circular economy
Recycling
Waste management
Value chain
Sustainable development
Circular business model

ABSTRACT

This study investigates plastic circularity in the EU automotive sector. It focuses on the drivers and barriers to recycling, informing the definition of policy options underlying the new *End-of-Life Vehicles Regulation* proposed by the European Commission in 2023. The analysis combines secondary data from scientific and grey literature, with primary data from industry stakeholders. Results include a supply chain map outlining stakeholders, industrial processes, and material flows, complemented by a list of 15 barriers and 8 drivers for increasing recycled plastic content in new vehicles. This study demonstrates how a supply chain perspective can effectively provide both systemic and granular insight about circular economy dynamics (i.e., big picture, high detail). Integrating these two levels of insight is crucial for advancing circular economy research and enhancing its ability to inform evidence-based policies for the sustainability transition.

1. Research background and objective

The current economic system is based on a linear paradigm, where resources are extracted, transformed into products, distributed on the market, used, and disposed as waste (Ellen MacArthur Foundation, 2013). Due to increasing resource extraction, production, consumption, and waste generation, the system is now operating beyond the Earth's carrying capacity (Rockström et al., 2009; Steffen et al., 2015). The circular economy represents an alternative model to decouple growth from unsustainable environmental impacts by optimizing resource consumption, minimizing waste and pollution (Blomsma and Brennan, 2017; Ellen MacArthur Foundation, 2013). The origins of this concept are rooted in the ecology domain and engineering views about resource efficiency and product life extension achieved by "closing the loop" of material flows through different strategies such reuse and recycling (Odum, 1973; Stahel, 1994).

In the past three decades, global efforts were conducted towards resource efficiency and circularity (Baldassarre and Saveyn, 2023; Belmonte-Ureña et al., 2021). The European Union (EU) also developed policy initiatives focusing on closing resource loops, which in 2015 converged into the first Circular Economy Action Plan (European Commission, 2015). A revised CE action plan was released in 2020—as a key part of the European Green Deal of president Von der Leyden's Commission—aiming to foster a climate-neutral, resource-efficient and more competitive economy (European Commission, 2019, 2020). Through this policy framework, the EU has the ambition to lead the circular economy transition on global level, focusing its efforts in the first place on identified priority sectors and supply chains, including: batteries and vehicles, electronics and ICT, packaging, plastics, textiles, construction and buildings, food, water and nutrients (European Commission, 2020a).

The circular economy transition, however, is a complex process. Despite increasing discussions and emergent legislation, waste generation and reliance on virgin materials remain overwhelmingly high, while the relative share of secondary materials entering the economy has decreases steadily between 2018 (9.1%) and 2023 (7.2%) (Circle Economy Foundation, 2024). Achieving circularity requires substantial and interconnected changes in the current socio-technical-economic system, transforming products, services, industrial processes, people's behaviors, and the business models of organizations across supply

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https://doi.org/10.1016/j.resconrec.2025.108216
Received 23 July 2024; Received in revised form 7 February 2025; Accepted 23 February 2025
Available online 6 March 2025

chains and market sectors (Esposito et al., 2018; Van Dam et al., 2020; Baldassarre and Micciché, 2014). Academic literature has identified the main barriers obstructing the circular economy transition, as well as the main drivers that might be leveraged to catalyse it. A recent scientific framework categorizes drivers and barriers as cultural, regulatory, economic, and technical (de Jesus and Mendonça, 2018; Kirchherr et al., 2018). An example of cultural driver is the awareness of people about the environmental harms of the current economic system. An example of regulatory barrier is divergent views across different governments and organizations on how to frame and implement actions to decouple resource consumption and other negative environmental impacts from economic growth. An example of economic barrier is the difference in price of virgin raw materials and secondary materials. An example of technical driver is a new process for recovering waste and turning it into the input for a new industrial process.

This literature is relevant to better understand and disentangle the variables to be considered in the circular economy transition. However, it has a high-level focus, which fails to capture specific key challenges occurring within different industries (Bilal et al., 2020). In other words, since every industry sector is different (e.g., market dynamics, stakeholders involved, production processes and materials), its transformation from linear to circular is characterized by different barriers and drivers (Agyemang et al., 2019). Granular insight at this deeper level is essential to better understand, and eventually overcome barriers, while leveraging the drivers (Agyemang et al., 2019; Bilal et al., 2020). New research aiming to identify specific circularity barriers and drivers related to different sectors, supply chains, geographical areas, and / or materials is rapidly emerging. For example, researchers identified drivers and barriers to circularity in the building sector (Hart et al., 2019), in the Brazilian coffee supply chain (Guimarães et al., 2022) and for flexible packaging recycling (Bening et al., 2021). To date, these efforts are still recent and restricted to a limited number of focus areas. A broad knowledge gap remains. Substantial research work is needed to fill it, and support more targeted, concrete actions toward circularity. This study focuses on a fraction of this knowledge gap, related to the drivers and barriers to plastic circularity in the EU automotive sector.

The EU yearly production of plastic waste has reached circa. 29.5 Mt/year, and is becoming increasingly difficult to manage (Plastics Europe, 2020, 2021, 2022). 9.7% of the overall plastic demand to manufacture new products comes from automotive, making this sector the third consumer after packaging and construction (Plastics Europe, 2020, 2021, 2022). Efforts to recycle plastics from vehicles are still limited. Existing initiatives from the automotive sector are already integrating minor shares of recycled plastic into new vehicles—estimated to be circa. 2.9%—leaving room to further increase plastics circularity in this sector (Plastics Europe, 2022). There is an opportunity to integrate a share of this plastic waste into new vehicles, through recycling. Relatedly, the EU Commission is currently reviewing the *end-of-life vehicles directive* (European Parliament and Council, 2000). The directive was first introduced in 2000, requiring Member States to reach the following targets by 2015: 95% reuse and recovery (on average per vehicle per year by weight); 85% reuse and recycling (on average per vehicle per year by weight). According to the fourth Commission report on its implementation (European Commission, 2020b), the directive had been satisfactorily transposed in national legislation. As of 2017, 14 Member States reached the recovery targets while others defined measures to achieve them. The evaluation also highlighted a key challenge related to end-of-life vehicles of unknown whereabouts, caused by illegal collection and trading practices, resulting in the loss of valuable resources and sub-optimal waste management. It also suggests the need to evaluate the feasibility and effectiveness of setting targets for specific materials. Following a review of the directive in 2021, in July 2023, the European Commission proposed a new *end-of-life vehicles regulation*, in line with the European Green Deal and Circular Economy Action Plan, which builds on the replaces the directive (European Commission, 2023b). The aim of the proposal is addressing the challenge by laying down a set of criteria to determine whether a used vehicle should be considered as an end-of-life vehicle. Moreover, an important objective of the proposal is tackling the lack of circularity in design and production (including automotive plastics parts) while increasing the quality and the quantity of vehicle waste flows and treatment processes. Vehicle design requirements are established as prerequisites for the effective implementation of end-of-life management provisions. This includes: strengthening the correlation between reusability, recyclability, and recoverability rates and the targets for reuse, recovery, and recycling; strengthening the connection between restrictions on certain substances in vehicles and the requirement to remove components containing these substances before shredding; emphasising the design of parts for easy removal to meet the obligation of removing specific components prior to shredding, as well as introducing a wide range of measures designed to improve the availability, quality and traceability of second-hand spare parts; increasing the alignment of recycled content requirements with plastic recycling targets (European Commission, 2023b). Setting recycled plastic content targets in new vehicles placed on the EU market is thus identified as relevant policy intervention (Maury et al., 2023), which goes hand in hand with the introduction of quality and traceability requirements to meet the objectives of the Circular Economy Action Plan and retain the highest possible material value (Gazeau et al., 2024). Reaching this complex industrial policy objective requires understanding the underling drivers and barriers to plastic recycling in automotive, as well as the supply chain context in which they occur, to ensure feasibility and verify that an appropriate level can be achieved (Baldassarre et al., 2022; Maury et al., 2023).

Relevant studies on the drivers and barriers to circularity in the automotive sector are present, however they focus on several materials without providing details related to plastics in vehicles (Agrawal et al., 2020; Agyemang et al., 2019). At the same time, while studies on the drivers and barriers to plastic circularity are present, their focus is either cross-sectoral or packaging (Antonopoulos et al., 2021; Bening et al., 2021; Milios et al., 2018; Paletta et al., 2019). In-depth research zooming on the drivers and barriers to plastic circularity within the automotive sector specifically is scant. Miller et al. (Miller et al., 2014) analysed the North American automotive sector and identified a set of barriers to plastic recycling, while also proposing a few alternatives to address them. More recently, van Bruggen et al. (van Bruggen et al., 2022) conducted a similar study with a focus on the barriers to plastic recycling and the reuse of plastic components within the Dutch automotive sector. The study also outlines potential solutions to overcome the barriers. Despite their relevance, these studies have some limitations. First, they focus mostly on barriers, without examining existing drivers, which is also important to catalyse a circular transformation (de Jesus and Mendonça, 2018). Second, they provide limited qualitative and quantitative insight on the supply chain context in which the barriers occur. Third, they are scattered in terms of geographical scope, while a comprehensive study at the EU level is not yet present.

To address these limitations, this article aims to provide a comprehensive overview of all the cultural, regulatory, economic, and technical barriers and drivers related specifically to plastic recycling in the EU automotive sector. The drivers and barrier are contextualized against complementary information on the supply chain structure, its stakeholder interactions, and a quantitative characterization of the underlying material flows. This is achieved by integrating the limited available information from academic literature with key insights from up-to date industry and policy reports, as well as primary data from stakeholder interviews. Our results include two main elements: a plastic supply chain map, outlining stakeholder interactions and main material flows within the EU automotive sector (Fig. 1); and a thorough list of 15 barriers and 8 drivers for increasing recycled plastic content in new vehicles, contextualized within the supply chain.

The contribution of these results is twofold. From a practice perspective, we provide insight into the current and future state of play

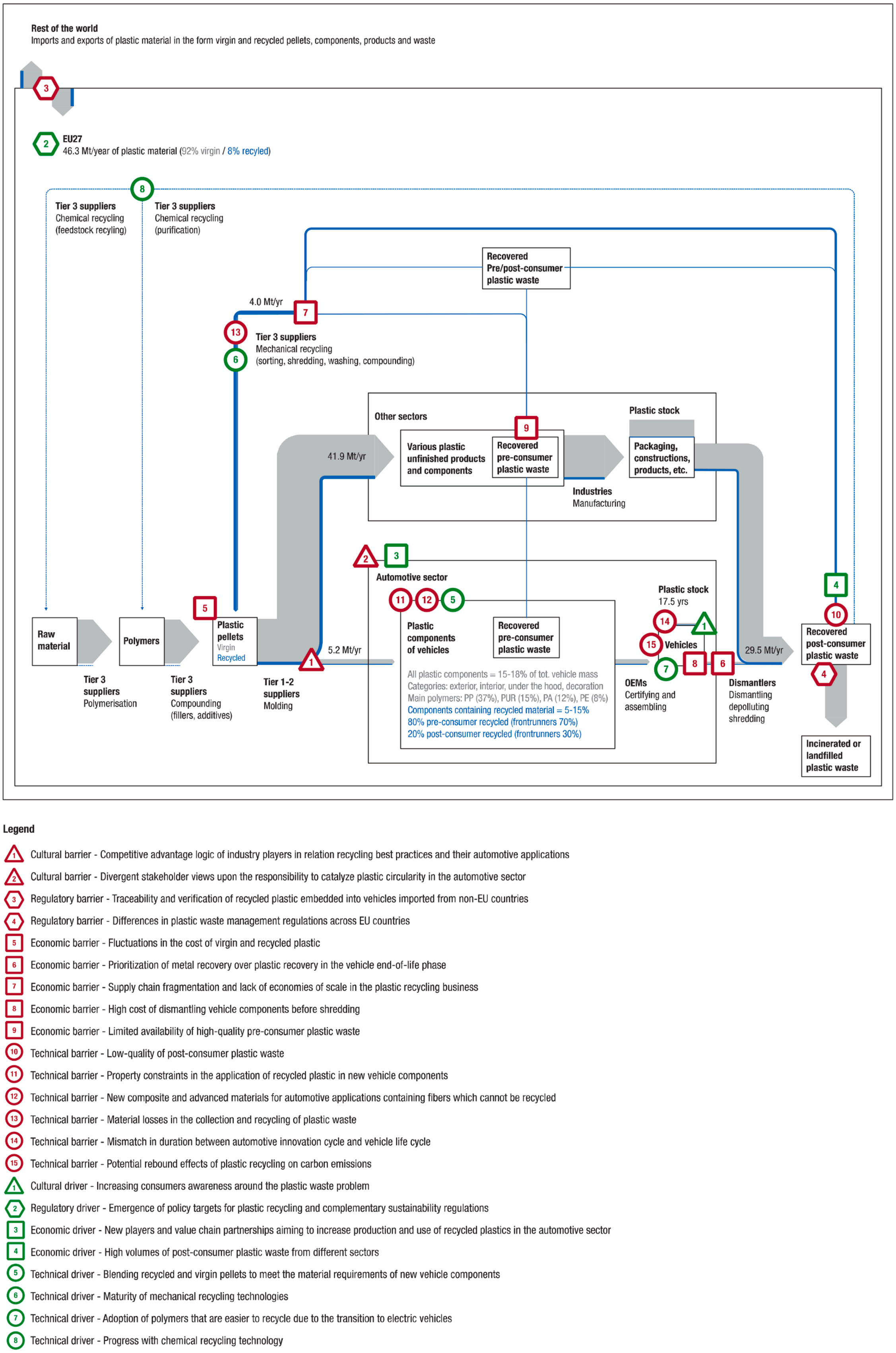


Fig. 1. Supply chain of virgin and recycled plastic in the EU automotive sector, including barriers and drivers to recycling. Based on literature and stakeholder inputs.

of plastic recycling in the EU automotive sector. This is relevant to inform policy interventions to increase plastic circularity. From a theory perspective, we illustrate how circularity drivers and barriers may be identified using the supply chain as a unit of analysis at the meso-level. This is relevant to address the limitations of both macro and micro-level studies, in view of providing a framing for future studies addressing the call for empirical research providing a comprehensive yet more granular understanding of the factors to be considered in the circular economy transition (de Jesus and Mendonça, 2018; Kirchherr et al., 2018).

2. Method

The European Commission has been exploring possibilities to increase recycled plastic content in new vehicles placed on the EU market. To support this aim, the *end-of-life vehicles directive* is currently being reviewed and updated into a new regulation (European Commission, 2023b; European Parliament and Council, 2000). The Commission's Directorate-General Joint Research Centre (JRC) has been involved with the task of consolidating data and knowledge on the subject, to support the policymaking process. In this context, the present study addressed a knowledge gap around drivers and barriers to plastic recycling in the EU automotive sector. The paper puts forward two main outcomes: a detailed visualization of the plastic supply chain, outlining stakeholders and main material flows within the EU automotive sector (Fig. 1); and a comprehensive list of 15 barriers and 8 drivers for increasing recycled plastic content in new vehicles, mapped on the supply chain at the location where they occur. The method to derive these outcomes is described below.

First, we performed secondary data collection through literature review. We compiled relevant data about the structure of the supply chain of virgin and recycled plastics, as well as on the quantitative (i.e., mass, plastic composition) and qualitative (i.e., polymer types) features of the material flows within. Specifically, data was retrieved from academic sources and grey literature including industry and policy reports produced by different actors including the Ellen MacArthur Foundation, Deloitte Sustainability, the United Nations Environment Programme, the European Commission, The Plastic Industry Trade Association, Plastics Europe, European recycling industries EuRIC, and the EU Circular Plastics Alliance (CPA).

Second, we integrated secondary data with primary data collected through semi-structured qualitative interviews (Patton, 2002) with key stakeholders in the supply chain. To capture a complete picture of the investigated subject at the EU level, selected stakeholders included various EU industry association, leading companies manufacturing vehicles and plastic components, plastic recyclers working with automotive waste, and independent experts. We developed interview-guide material, including a written list of questions related to the supply chain structure (i.e., quantitative and qualitative features of the material flows, industrial processes and stakeholder interactions) and to the cultural, regulatory, economic, and technical barriers and drivers to circularity structured according to former scientific literature (de Jesus and Mendonça, 2018; Kirchherr et al., 2018). Interview questions were iteratively refined and detailed throughout the data collection process. The interview guide also included a preliminary sketch of the supply chain based on available data. The interview guide is reported in appendix A. We consequently conducted the interviews, actively discussing proposed questions with stakeholders and taking written notes while gradually enriching and validating the literature-based supply chain sketch. Interviews were also enriched by plants visits as well as complementary feedback from a joint workshop for a multilateral exchange with representatives from the different stakeholder groups in the supply chain. Table 1 contains the list of our primary data sources.

Third, we analysed primary and secondary data, condensing them into our results. To this end, we employed visualization techniques and a coding method (Fereday and Muir-Cochrane, 2006; Miles et al., 2013). Passages of text, figures and diagrams from the selected literature were processed and integrated to derive a "network type" visualization of the supply chain including its steps, stakeholders, and material flows of virgin and recycled plastics (Miles et al., 2013). In parallel, written interview notes containing raw data on the drivers and barriers were coded into a clean list of 15 barriers and 8 drivers (Fereday and Muir-Cochrane, 2006). The coding scheme is reported in appendix B. This entailed going through all the written notes in an iterative manner, gradually clustering relevant inputs into emergent themes (i.e., codes—represented by the proposed list of drivers and barriers). This process guided by former research to categorize drivers and barriers according to their cultural, regulatory, economic, and technical nature (de Jesus and Mendonça, 2018; Kirchherr et al., 2018). To mitigate bias and ensure validity and reliability of these results, two researchers in the author team performed data analysis in parallel and separately. Independent results were consequently discussed and integrated with the inputs of other authors. Finally, the identified drivers and barriers were mapped onto the supply chain visualization using different shapes and colours to distinguish them.

Table 1
Primary data sources.

Ref.	Stakeholder Type	Stakeholder Focus
[A]	Industry association 1	Vehicles
[B]	Industry association 2	Vehicle components
[C]	Industry association 3	Plastic
[D]	Industry association 4	Plastic recycling
[E]	Industry association 5	Plastic recycling
[F]	Manufacturer 1	Vehicles
[G]	Manufacturer 2	Vehicles
[H]	Manufacturer 3	Plastic components for vehicles
[I]	Recycler 1	Plastic
[J]	Recycler 2	Plastic
[K]	Recycler 3	Plastic
[L]	Recycler 4	Plastic
[M]	Recycler 5	Plastic
[N]	Expert 1	Plastic recycling / Vehicles
[O]	Expert 2	Plastic recycling / Vehicles

3. Results

This section presents our results concerning the supply chain of plastic within the EU automotive sector. In Section 3.1, we outline the supply chain, including a descriptive overview of its main stakeholders and material flow. In Section 3.2 we list and describe the barriers and drivers to increase recycled plastic content in new vehicles. These results are visually summarized in Fig. 1.

3.1. Description of the supply chain

Fig. 1 shows the EU supply chain of virgin and recycled plastic embedded in new vehicles. Material flows of virgin plastic are visualized in grey, while recycled plastic flows in blue. The thickness of the flows provides a visual—indicative—representation of where the largest volumes lie. Plastic material may be exported or imported in the EU at different stages of the supply chain, in the form of virgin and recycled pellets, components, products and waste. Import and export flows are visualized in the top-left corner of the figure.

Upstream in the supply chain, raw materials (i.e., crude oil and natural gas) are processed into polymers by tier 3 suppliers. Polymers are mixed with different fillers and additives in a compounding process, resulting into plastic pellets with different specifications. Tier 2 suppliers (i.e., supplying across sectors) and tier 1 suppliers (i.e., supplying only the automotive sector) turn pellets into different components for new vehicles with different moulding processes. Plastics components can be categorized according to four types of applications: exterior (e.g., bumpers), interior (e.g., dashboard), under the hood (e.g., engine cover), decorations (e.g., wheel covers). Altogether, these components represent 14–18% of the a vehicle mass (inputs from stakeholders) (Circular Plastic Alliance, 2020, 2021a, 2021b). The main polymer types used in passenger car applications are PP (37%), PUR (15%), PA (12%), PE (8%), PVC (7%), ABS (7%), PET (5%) and others including PC, PMMA, PBT, POM (9%) (inputs from stakeholders) (Emilsson and Dahllöf, 2019; The Plastics Industry Trade Association, 2016).

In the middle of the supply chain, original equipment manufacturers (OEMs) assemble the vehicles. OEMs in the automotive sector are accountable for a demand of 5.2 Mt/year of plastic, which is roughly 9% of the aggregated demand from all sectors (3rd sector after packaging and construction) (Plastics Europe, 2020, 2021). They source plastic components from suppliers, certify suitability for automotive application, and assemble them into the final product. The vehicle is then put on the EU market, where it is used for approximately 17.5 years (inputs from stakeholders). During this period, the plastic embedded in the vehicle is considered as material “stock” within the sector.

Downstream in the supply chain, at the end of the use phase, the vehicle is collected in authorised treatment facilities where it is depolluted, dismantled, and shredded. After shredding, metals are recovered first. Plastic shreds are considered less valuable and include a mix of different polymers (inputs from stakeholders). In most cases, plastic shreds from vehicles are also merged with additional plastic shreds or waste from other sectors. The total amount of plastic waste generated in the EU by all sectors amounts to 29.5 Mt/year (Plastics Europe, 2020, 2021, 2022). After collection, it is either recycled, incinerated for energy recovery, or disposed into landfill. Regarding plastic waste from vehicles: 19% is sent to recycling, 41% is used for energy recovery and 40% is disposed into landfill (inputs from stakeholders).

The total amount of recycled plastic used in new products in the EU amounts to 4.0 Mt/year (Plastics Europe, 2020, 2021). In the automotive sector, the demand of recycled plastic comes from OEMs through their suppliers (Tiers), mainly driven by a cost-saving rationale, and by the need of responding to market trends such as increased consumer awareness to sustainability issues or OEM sustainability strategies to reduce CO_2 footprint of vehicle. OEMs might not always be aware of the recycled plastic content in their sourced plastic flows (inputs from stakeholders). The technical specifications of their purchase to suppliers are result-oriented (performance, colour, aesthetics, etc.) without considering the constraints of plastic blending processes. Accordingly, tier 1 and tier 2 suppliers, source recycled material from recyclers (tier 3 suppliers specialized in the production of plastic pellets from waste) and integrate it in the plastic parts and components to be sent to OEMs. Plastic recyclers perform a mechanical recycling process based on several steps: collecting plastic waste; separating polymer types (when possible); shredding (if not already shredded); separating shreds to reach an output as homogeneous as possible (commonly based on wet density sorting techniques); compounding and blending the output (by melting it in combination with fillers and additives); extruding recycled pellets. In most cases, these steps are not performed by a single business. The total mass of the recycled plastic in a vehicle (considering both pre-consumer and post-consumer plastic waste), ranges from 0% to 15%, depending on model and brand. In some cases, it can even reach 20% (inputs from stakeholders). Still, pre-consumer plastic is the predominant source for the recycled content.

Virtually all recycled plastic embedded in a new vehicle is obtained through mechanical recycling. About 80% comes from pre-consumer waste (i.e., waste generated during disparate industrial production process in different sectors), which is more homogenous and easier to recycle. On the other hand, post-consumer plastic, although it represents most of the waste, it is recycled to a very limited extent. Only 109 kt of post-consumer recycled plastic is entering the automotive sector annually in the EU (Deloitte Sustainability, 2017; Plastics Europe, 2020, 2021; Watkins et al., 2020). Relatedly, 20% of recycled plastic embedded in a vehicle currently comes post-consumer sources (i.e., plastic waste from used products e.g., packaging). Precise estimates are difficult to get. These percentages provide a rough indication (based on inputs from stakeholders). Making a more accurate estimate is challenging because before being integrated into a new vehicle, pre-consumer and post-consumer plastic waste is sometimes mixed in the collection step and sometimes blended with virgin material in the compounding step of mechanical recycling.

Chemical recycling represents an alternative to overcome the limitations of the mechanical process, turning post- consumer waste back into new polymers (purification) or even into raw material (feedstock recycling). However, chemical recycling can have very high environmental impacts, and may only be interesting for specific waste streams. It still requires significant R&D before it can be implemented on the market at full scale (Circular Plastic Alliance, 2020). For this reason, the flow of chemically recycled plastic is visualized in Fig. 1 with a discontinuous, dashed, blue flow.

3.2. Description of barriers and drivers

Fig. 1 shows the barriers and drivers for increasing recycled plastic in new passenger cars in the EU. These barriers and drivers were identified through the interviews with selected stakeholders, and accordingly numbered and mapped upon the supply chain diagram to indicate the location where they occur. Different colours and shapes were used to distinguish them. Red triangles represent cultural barriers, red squares regulatory barriers, red hexagons economic barriers and red circles technical barriers. Drivers were mapped with the same logic, using the green colour.

3.2.1. Barrier 1 (cultural) – competitive advantage logic of industry players in relation to recycling best practices and their automotive applications

This hinders knowledge transfer across industry players regarding available options of recycled material. Compounding recipes and simulation software are for recyclers sources of competitive advantage not to be shared with competitors and clients [H, J, K], while vehicle manufacturers are also concerned with confidentiality of the material used in their components [A, G, H].

3.2.2. Barrier 2 (cultural) – divergent stakeholder views upon the responsibility to catalyze plastic circularity in the automotive sector

Stakeholders in the automotive sector and recycled plastic supply chain have different views on who should be responsible for catalyzing the transition towards circularity. Vehicle manufacturers maintain that technological change should start with recyclers, the chemical industry, and the suppliers of the components [A, G]. Component manufacturers also expect solutions to come from upstream [B, H]. Moreover, like recyclers, they also consider vehicle manufacturers downstream to be responsible for creating consumer demand [B, H, J, K, N]. Plastic recycling is not considered in extended producer responsibility schemes and thus is financially supported by recyclers only [I, N]. Finally, all stakeholders expect the change to be driven by policymaking, especially recyclers who see targets as an opportunity to strengthen their business [L, M, N]. However, policy action is largely driven by the need to deal with increasing post-consumer plastic waste, while manufacturing companies are not particularly concerned about the distinction between pre- consumer and post-consumer plastic since their sustainability targets simply consider recycled content [A, N].

3.2.3. Barrier 3 (regulatory) – traceability and verification of recycled plastic embedded into vehicles imported from non-EU countries

Regulating the amount of recycled plastic to be embedded in new vehicles sold on the EU market is challenging due to complex import-export dynamics. Tracing and verifying recycled content embedded into products and component imported from outside the EU is for the time being hardly feasible [D]. EU manufacturing companies in the automotive sector are not worried about the provenance of the materials they use, since they trust their own suppliers mainly based in the EU or MENA region, nonetheless they are concerned about their ability to compete with non-EU companies who might not always comply with upcoming regulations [A, B, F, N]. To address these valid concerns and not decrease the competitiveness of EU industry, it is essential to create traceability and verification schemes to distinguish between post and pre consumer plastic, as well as their different quality [D]. To ensure EU competitiveness, such systems should be implemented worldwide, which is difficult [D]. Important aspects of the traceability challenge are the diversity of automotive components and the mixing of secondary plastic material with virgin material, additives, and fillers within the recycling process [F, K].

3.2.4. Barrier 4 (regulatory) – differences in plastic waste management regulations across EU countries

Plastic waste is managed differently across EU countries, due to different national regulations [C, D, E]. For example, there are countries that are not in favor of incineration and prefer to make use of landfills even if they are in principle a less suitable option [E]. At high level, the EU countries that are dealing most successfully with plastic waste, still incinerate around 50% of it, while recycling most of the remainder and making very little use of landfills [C]. On the other hand, EU countries that are not performing so well, still send 60% or more of their plastic waste into landfills, while incinerating the rest and recycling only a fraction of it [C]. The current recycling rate of plastics from end-of-life vehicles is estimated at 19% because large amounts of material are incinerated or dismissed in landfills [C, D, E]. This results into serious environmental impacts, in terms of pollution but also due to substantial carbon emissions from incineration, which could be avoided by increasing recycling [N, O]. From an environmental perspective, recycling is a better option than energy recovery from incineration, however the uptake of recycling at the EU level is challenging because recycling infrastructure differs greatly across countries [D].

3.2.5. Barrier 5 (economic) – fluctuations in the cost of virgin and recycled plastic

The cost of virgin plastic is influenced by changing oil prices, while the cost of recycled plastic is influenced by several factors, including availability, sourcing channels, different separation methods, and testing [B, K, L]. Testing can be expensive because it is influenced by the composition of the plastic waste batch, which changes constantly [K]. These fluctuations make it challenging for vehicle manufacturers to assess when it would be convenient to choose recycled over virgin plastic, resulting in the lack of a solid business case [A, F, G]. When oil prices decrease, virgin plastics becomes cheaper. For example, a vehicle manufacturer reports that, sometimes, using recycled PET for the textiles in the interior of the cars is more expensive than using virgin PET [F].

3.2.6. Barrier 6 (economic) – prioritization of metal recovery over plastic recovery in the vehicle end-of-life phase

At the end-of-life, vehicles are depolluted, removing parts containing liquids and toxic material, and then they are shredded altogether very quickly using machines that are not particularly sophisticated [J]. This results in mix of material, including metal, plastic and other [M]. Metal is then easily recovered using different methods, including eddy-current separation based on magnetic field [L]. Metal recovery is prioritized over plastic recovery because it is more economically attractive [J, K]. From an environmental perspective, metal recycling (especially aluminium and steel) is highly relevant to achieve decarbonisation objectives. The same applies to plastic recycling. However, plastic recovery and separation from the mix is a lot more challenging, with no straightforward business case in place, rending its recovery less economically attractive [J, K]. Post shredding technologies (PST), able to sort higher quantities of plastic flows are also not deployed uniformly at European level. To change that, the approach on how vehicles are designed and dealt with at the end-of-life should change to make plastic recovery and separation a priority [J, K].

3.2.7. Barrier 7 (economic) – supply chain fragmentation and lack of economies of scale in the plastic recycling business

The business of plastic recycling from end-of-life vehicles is still relatively new, with many highly specialized small players who operate at the niche level and lack the economies of scale to expand their operations and transform the market toward circularity [D, J, K, M]. The different steps in the supply chain, including waste collection, sorting, grinding, reprocessing, and compounding, are often performed by different companies with different expertise [J, K]. Most recycling companies are not big enough yet to cover all steps because the equipment and software needed is very specific and expensive, requiring significant capital investments [I, J, K]. Without large volumes of recyclable plastic supporting the business case, emerging recyclers cannot scale up, while incumbent suppliers of virgin plastics have not yet entered this space, due to the challenges involved [D, M, N].

3.2.8. Barrier 8 (economic) – high cost of dismantling vehicle components before shredding

Vehicle components could be in principle dismantled a first step at the end of-life, to recover plastic that is homogenous in composition before it gets mixed in the shredding process [A, B, C]. However, doing so would take a lot of time, making the option not economically viable [D, L, M]. For some of the larger components, such as bumpers, fuel, and water tanks, it is technically feasible, but even with them the business case is very challenging to put in place [L]. To make dismantling possible in the EU, modular design is needed, as well as a narrower spectrum of materials used, and lighter components [N, O]. EPR schemes could also in principle support dismantling efforts. For the time being, some of the valuable components that are in good conditions at the end-of-life, for example the doors, are sometimes extracted for reuse and sold to non-EU countries [M].

3.2.9. Barrier 9 (economic) – limited availability of high-quality pre-consumer plastic waste

Pre-consumer plastic waste from disparate manufacturing processes is homogenous, it has a high-quality and is suitable for recycling [D]. However, it is available in limited quantity and should decrease with time thanks to higher manufacturing performances [D, M]. This can lead to supply chain bottlenecks, potential manufacturing shortages and thus to a sourcing competition, both within recyclers and firms in the automotive sector, and across sectors [A, B, J, M]. Furthermore, homogeneous pre-consumer plastic waste is often mixed with diverse post-consumer waste leading to inefficiencies in the recycling industry [B, D, J, L]. Increasing recycling rates of pre-consumer plastic waste is possible and result into important environmental benefits, including a reduction in carbon emissions and resource use through avoided virgin production [N, O].

3.2.10. Barrier 10 (technical) – low-quality of post-consumer plastic waste

Post-consumer plastic waste is affected by quality issues, which make it hard to recycle [B, E]. Aged plastic is often degraded and unsuitable for recycling [B, D]. The high diversity in the composition of post-consumer waste makes the separation of different plastic types extremely challenging, hindering the possibility to achieve high-quality recycled polymers [B, D, L, M]. The batches of post-consumer plastic periodically sourced by recyclers are unstable, meaning that their composition changes from time to time, but can be overcome during the blending process [B]. Implementing appropriate auditing, certification or traceability schemes should help overcome quality issues, a key topic that deserves attention going forward [D]. Contaminants such as impurities, hazardous substances, and volatile organic compounds represent a critical quality issue, resulting in deviation from optimal recycling routes, hence negative environmental impacts [E, G, L, M]. It is estimated that the level of contamination of plastics from EU shredded end-of-life vehicle are below pollutants thresholds. Better vehicle design options and the development of recycling practices should also in principle lower such contamination, and reduce emissions through avoided virgin production [G, H, I]. The latter aspects, which also applies to pre-consumer plastic waste, is particularly important for post-consumer flows, given the superior volumes and complexity in handling it.

3.2.11. Barrier 11 (technical) – property constraints in the application of recycled plastic in new vehicle components

The use of recycled plastics in the production of components for new vehicles is radically limited by safety, performance, and aesthetics requirements [C]. Several components need to have specific mechanical, thermal and optical properties found in sophisticated polymers such as ABS, PC and specific grades of PA [A, B, G, H, J]. Such polymers are often complex to recycle, for different reasons [B]. Furthermore, the use recycled plastic in the interior of the vehicle can compromise customer desirability, due to poor aesthetic look and odour issues [F, H]. Finally, there are no clear standards and one-fits-all solution since requirements differ component by component, vehicle model and brand [A, K, H].

3.2.12. Barrier 12 (technical) – new composite and advanced materials for automotive applications containing fibres which cannot be recycled

Automotive industry manufacturers are using multi-layer plastic materials or new composite materials, including polymers containing natural fibres from coconut or cellulose [F, H]. The rationale is increasing mechanical performance while having a lighter vehicle that can be positioned on the consumer market as a sustainable product [A]. However, these composite materials cannot be recycled using conventional processes because the fibres blend into the plastic matrix permanently and also compromise the quality of the overall plastic flow from vehicles, potential resulting in negative environmental impact at the end-of-life [M].

3.2.13. Barrier 13 (technical) – material losses in the collection and recycling of plastic waste

There is a very large gap between the plastic products, including vehicles, that are collected at their end-of-life, and the plastic that enters a shredder to be recycled [C]. There are losses in the collection process. Furthermore, losses also occur in the sorting and recycling processes, in the shredding as well as in the compounding steps [E, L]. In some recycling plants, losses can be estimated at around 10% [M].

3.2.14. Barrier 14 (technical) – mismatch in duration between automotive innovation cycle and vehicle life cycle

The average lifetime of a vehicle is 15–20 years. There is a long gap between the design and production of vehicle components and their end-of-life [A, G]. Design-for-recycling interventions introduced now will only have an effect in several years [C, L]. Moreover, the matter is complicated by evolving regulations on plastic materials suitable for vehicles, encompassing for example mechanical properties and toxic substances, and by the transition to electric vehicles, which is bringing about changes in components and composition [A, B, G]. These quick changes make it challenging for manufactures to adapt and take future recyclability into account [C].

3.2.15. Barrier 15 (technical) – potential rebound effects of plastic recycling on carbon emissions

Rebound effects might arise due to increased plastic circularity in the automotive sector [B, C, E]. Despite increasing the share of recycled plastic is functional to achieve decarbonisation objectives (through avoided virgin production), using more recycled plastic in new components may require increasing the overall plastic mass to, for example, increase mechanical resistance, which would in turn result in a heavier vehicle and higher carbon emissions in the use phase [A, B]. Therefore, trade-offs must be considered carefully, while also factoring in the carbon emissions of the recycling process itself, which to be sustainable should be powered with renewable energy [C, E, M, O].

3.2.16. Driver 1 (cultural) – increasing consumers awareness around the plastic waste problem

People's awareness of global sustainability issues, including climate change but also the plastic waste problem is increasing quickly, putting pressure on companies [C]. Consumer awareness on plastic pollution represents one of the main drivers for manufacturers to introduce recycled content in new vehicles [A, F, G]. Although consumer awareness of the connection between recycled content and carbon emissions is less prominent, this may be another driver in corporate sustainability strategies for reducing the environmental footprint in automotive [A, F, G]. Doing so, directly affects brand value, even though return on investment is difficult to quantify [A, F, K]. Thus, recycled plastic appears as an item within the list of requirements in the purchase orders of vehicle manufacturers, since it is becoming a competitive issue dealt by upper management when discussing the high-level sustainability strategy of the organization [A, F, H].

3.2.17. Driver 2 (regulatory) – emergence of policy targets for plastic recycling and complementary sustainability regulations

Policy targets for plastic recycling are emerging. They are largely motivated by the need to deal with ever increasing post-consumer plastic waste and plastic pollution [C]. While it is important to keep them technology and material neutral, they are expected to speed-up recycling technology development and its market application by standardizing recycled output and ensuring its constant quality [A, N]. Policymaking is advancing especially in the packaging sector [C]. In the automotive sector such targets have the potential to force demand of recycled plastic from automotive companies, while considerably supporting recycling firms to grow and shape the market [K, L]. On the environmental side, carbon pricing is an essential mechanism to create new economic incentives by boosting the value of recycled polymers material, while emerging certifications for biobased materials could be used as a blueprint and replicated for mechanical recycling [F, G].

3.2.18. Driver 3 (economic) – new players and supply chain partnerships aiming to increase production and use of recycled plastics in the automotive sector

Supply chain partnerships make it possible to drive plastic circularity in the automotive sector. Some important partnerships are already in place. By working together for several years, some recyclers and leading vehicle and component manufacturers have become able to trust each other and find joint solution to significantly increase the amount of recycled plastic content embedded in new vehicles [G, J, M, L]. Collaboration with research institutes also play an important role in this regard [C]. Furthermore, next to the historical players with expertise on plastic separation and mechanical recycling, new entrants are now starting to focus on complementary solutions, mostly chemical recycling [D, G, K].

3.2.19. Driver 4 (economic) – high volumes of post-consumer plastic waste from different sectors

Large amounts of post-consumer plastic waste from other sectors can be sourced by the automotive sector, to foster open loop recycling. The estimations derived from the mass and flows models indicate that there is a huge plastic waste stock embedded in end-of-life vehicles but also in other sectors such as, packaging, building and construction, electrical and electronic equipment [C, K]. This results in a big market opportunity for inter-sectorial exchange with the automotive sector, which could source it and use it to manufacture recycled components [F, N]. For example, PET fibres could be sourced from the 60% share of plastic bottles that are currently not recycled in the EU, to produce textiles for the car seats [A, F, G].

3.2.20. Driver 5 (technical) – blending recycled and virgin pellets to meet the material requirements of new vehicle components

Plastic waste can be blended with virgin polymer pellets and chemicals, also called boosters, in the compounding process. Recycled content can range between 30% and 90% [B, K]. Boosters represent a good, market-ready solution to make use of post-consumer plastic waste and make it suitable for automotive applications, especially in terms of mechanical and thermal properties [G, M]. Next to their environmental relevance for increasing the shares of recycled content, boosters offer new opportunities also with regards to aesthetics. For example, recycled content can be blended with other materials such as stones or oyster shells to achieve new colours, patterns, and textures for the interior of the car [G].

3.2.21. Driver 6 (technical) – maturity of mechanical recycling technologies

The mechanical recycling processes of many plastic grades is technologically mature and already contributes to improving the environmental performance in the sector. Material separation technology has been implemented on the market already since the 1980s [E]. Materials can be in principle separated efficiently and at a quick rate [M]. Next to this, new digital technologies now allow to model in advance recycled output, allowing to save time while reducing uncertainties related to its properties and costs [I, J]. Despite some challenges related to the numeric data needed for their implementation, such simulations models are applied successfully by recyclers [H]. Because of this, EU production capacity of recycled plastic might be increased with rather limited financial investments, resulting in important environmental gains [C].

3.2.22. Driver 7 (technical) – adoption of polymers that are easier to recycle due to the transition to electric vehicles

The shift to electric vehicles will likely result into an increase of components made with "easy-to- recycle" polymers. PP is currently the easiest polymer to recycle. Recyclers place a large focus on PP, about 50% of their production volumes, because when it is not mixed with fillers and additives, it can be easily separated from other polymers in a flotation tank, becoming relatively inexpensive to recycle [B, G, J, K]. Currently, PP is used for about 6% of the plastic mass of a vehicle, within basic parts that are hidden and have no technical requirements [G]. Also due to its superior recycling potential (hence theoretical environmental performance), the use of PP in electric vehicles is expected to increase, because they run at lower temperatures, making it a valid substitute for PA in under the hood components [G].

3.2.23. Driver 8 (technical) – progress with chemical recycling technology

Chemical recycling is a promising option, encompassing several technologies, to deal with plastic-waste on the way forward [C, N]. It is a complementary solution next to mechanical recycling, which can be used to deal with aged post-consumer plastic waste, allowing high quality applications such as safety components [G], K, [L]. R&D in this space is increasing quickly, however chemical recycling maturity is still low, and 10 years might still be needed to demonstrate its technical and economic feasibility [G]. Chemical recycling for PET and PUR polymers might be the closest to market readiness, but it is becoming clear that chemical recycling still requires waste separation and appears well suited only for very targeted and niche applications [B, G, L, M]. Finally, its environmental performance and competitiveness should also be carefully assessed, since the process is energy intensive, and the use of renewable is important to reduce its emissions and make the process fully sustainable [C].

4. Discussion

4.1. Contribution to circular economy EU policy

The results of this study directly contribute to EU policymaking by supporting the objectives of the current Circular Economy Action Plan (European Commission, 2020a), which prescribes to transform the most resource intensive and impactful economic activities, including the production of vehicles and the management of plastic waste. The results of the study were leveraged by the Joint Research Centre of the EU Commission to propose potential policy interventions to increase recycled plastic content in the automotive sector, in the context of the review of the *end-of-life vehicles directive* into a new regulation (European Commission, 2023b; European Parliament and Council, 2000).

The supply chain analysis provides a general state of play and outlook of the use of plastics materials and plastics recycling in the EU automotive sector. Based on the analysis we note that currently the market average upper bond's uptake of recycled plastic in a new vehicle is around 8%, including only 2% to 3% of post-consumer material (corresponding to around 4 kg for an average vehicle mass). From a closed-loop circularity perspective, this is a rather limited contribution, considering the overall quantity of plastic waste generated at end-of-life stage of a vehicle (>100 kg). On the other hand, we note that some leading car manufacturers (and their suppliers) are already able to integrate around 20% of recycled thermoplastic material (~36 kg), in a new vehicle. By 2030, the market average of recycled plastic in a new vehicle might increase significantly, supported by innovation, progress with technology and environmental claims. Better quantity and quality of recycled plastics from end-of-life vehicle stream might become available. While the shift towards e-mobility should not change dramatically the trends in using plastics materials in vehicles, some easy-to-recycle thermoplastics such as PP could be favoured compared to more expensive polymers presenting a higher thermal resistance. However, a future increase in recycled plastic in new vehicles put on the EU market is not straightforward and it could trigger disequilibrium between recycled plastics demand in the sector and available supply from the recycling market. A larger availability of end-of-life vehicle material flows, coupled with an increasing variety of polymers embedded in new vehicles is expected to pose recycling challenges. Bearing this in mind, we emphasize that the transition to increased plastic circularity in automotive will require interventions on multiple parallel level, as suggested by scientific literature on the subject and in line with the EU waste hierarchy (European Parliament and Council, 2008; Kirchherr et al., 2017, 2023). Going forward, mechanical and chemical recycling technologies may play a complementary role, considering their requirements as well as the limited maturity and current uncertainties around the full-scale deployment of the latter (Lase et al., 2023). From an economic perspective, the sustainable deployment and scaling of these technologies will require managing the balance between virgin and recycled plastic prices, which are influenced by fluctuating oil prices and the demand for secondary materials driven by regulations. A shift to renewable energy may reduce oil prices in the long run, lowering the cost of virgin plastics. Moreover, increased demand for secondary materials, spurred by circularity policies, could drive up the price of recycled plastics in the short term. Considering these issues is important, requiring attention, further investigation and potentially investments in the automotive supply chain to prevent additional R&D and production costs for vehicle manufacturers and their suppliers when using recycled plastics. Relatedly, design for recycling practices and standards should be strengthened going forward to avoid a decrease of recycling yields. Their implications for automotive applications require further study. In parallel, a systematic deployment of post-shredding-technologies will be needed to increase quality and quantity of plastics materials recycled from shredded vehicle's plastics-rich fractions. A study supporting the review of the *end-of-life vehicles directive* suggests that less than 10% of auto shredders are equipped with PST, these facilities being concentrated in only few countries in Western Europe (Trinomics, 2020). Finally, pre-processing operations such as dismantling should also increase the recovery of plastics from end-of-life vehicles, and could be a transitory option, particular in countries where labour costs remain limited. This type of intervention, despite the economic and cultural barriers it faces, could be functional not only for recycling but also for the reuse of vehicle components in view of new extended produced responsibility schemes and circular business models (e.g., remanufacturing), which have the potential to significantly reduce environmental impacts (Diaz Lopez et al., 2019; Soo et al., 2021; Vimal et al., 2022).

These insights and proposed systemic overview are functional to provide policymakers with a "bigger picture" needed to see and act upon specific leverage points to trigger interactions and chain reactions for circularity. This contribution resonates with recent circularity research emphasizing the importance of adopting a systemic perspective, identifying leverage points and chain reactions for a collaborative circularity transformation (Brown et al., 2019; Chakori et al., 2021; Arcipowska et al., 2024; Kirchherr et al., 2018). In this sense, the identification of specific cultural, regulatory, economic, and technical drivers and barriers provides essential granular details, supporting more informed and targeted circularity interventions. From an EU policy perspective, it is functional to substantiate potential interventions to solve circularity failures related to end-of-life vehicle. In line with the EU *better regulation guidelines*, which prescribe to adopt a participatory and evidence-based approach, the stakeholder inputs, drivers and barriers were leveraged to develop a SWOT (strength-weaknesses-opportunities-threats) analysis, visualised in Table 2.

This SWOT analysis, and the underlying supply chain study, drivers and barriers were functional to derive three policymaking criteria in the context of the new *end-of-life vehicle regulation proposal* (European Commission, 2021a, 2023b). The criteria include the ambition, timeline, and scope of the policy options.

4.1.1. Ambition of the policy intervention

A first criterion to consider is the ambition of the policy intervention. According to the *better regulation guidelines*, interventions can vary in nature, ranging from a soft regulatory approach to mandatory information and performance requirements. Taking into consideration all the challenges identified to achieve plastic circularity in the automotive sector from a cultural [barrier 1–2], as well as regulatory [barrier 3–4], economic [barrier 5–9] and technical [barrier 10–14] standpoint, it was deemed appropriate to introduce a degree of variation in ambition of proposed policy interventions. Accordingly, it is recommended the introduction of non-binding economic incentives to integrate recycled plastic content, next to declarations around recycled plastic content for new vehicles placed on the market, as well as embedded recycled plastic content targets. This degree of variability is functional to prevent sectorial shocks while fostering the circularity transition in automotive by enabling different industry players to gradually act and leverage catalysing factors [driver 1–8] based on their position in the supply chain and actual possibilities.

4.1.2. Timeline of the policy intervention

A second criterion to consider is the timeline of the policy intervention since the date of entry into force of regulatory mechanisms is a crucial factor to consider. The greater the ambition of the policy intervention, the longer adaptation time may be required by OEMs and their suppliers to meet the requirements. Considering the mismatches between product development and innovation cycles in automotive [barrier 14], as well as the time needed to address recycled plastic property constraints by design [barrier 11], it is advised to balance the ambition with an appropriate timeline. A preliminary and lower target could be set at short-term (e.g., 3 to 5 years after adoption) as a pilot followed by a monitoring period and ideally accompanied by an economic reward mechanism, which would also act synergistically with brand image

Table 2
Strengths, weaknesses, opportunities, and threats related to increasing recycled plastics in new vehicles in the EU.

INCREASING RECYCLED PLASTICS IN THE EU AUTOMOTIVE SECTOR			
STRENGHTS	**WEAKNESSES**	**OPPORTUNITIES**	**THREATS**
Frontrunner car manufacturers (and their suppliers) are currently able to integrate around 20% of recycled thermoplastic content (~36 kg), in a new vehicle.	**The market average of recycled plastic content in a new vehicle is currently around 8%, including only 2.5% of post-consumer material (4kg), which is a very limited contribution compared to the quantity of plastic waste generated at ELV stage (>100 kg).**	**The market average of recycled plastic content in a new vehicle might increase significantly by 2030, due to innovation and progress with technology.**	**A future increase in recycled plastic content in new vehicles on the EU market is not straightforward with potential risks of severe disequilibrium in both recycling and automotive markets.**
The incorporation of recycled plastic materials into new vehicles appears to be driven by strategic decision-making, economic benefits, and sustainability outcomes.	The use of recycled plastic material in automotive applications faces property limitations, such as lifespan, performance, and safety.	The transition to electric vehicles is expected to lead to an increase in the use of components made from "easy-to-recycle" polymers, such as polypropylene (PP).	An increase in recycled content in new vehicles could raise the weight of certain parts, potentially leading to rebound effects with higher carbon emissions throughout the vehicle's lifecycle.
Vehicle manufacturers are competing to incorporate recycled plastics to enhance their sustainability reputation and brand image.	The age of post-consumer plastics recovered from end-of-life vehicles can lead to quality and safety concerns, while the supply of pre-consumer waste is scarce.	R&D in chemical recycling technology is advancing at a rapid pace.	The fluctuations and decreases in oil prices over time could result in lower costs for virgin plastics, increasing R&D and production costs for vehicle manufactures using recycled plastics.
Collaborative partnerships within the supply chain are already in place to support the production and integration of recycled plastics in new vehicles.	The variety of plastic types and grades used in car components is extensive, with some containing fibres, which limits recycling options.	Post-consumer plastic waste from various sectors is available in large quantities and could promote open-loop circularity.	New composite materials with limited recyclability for automotive applications are being introduced.
The mechanical recycling methods for various plastic grades are technologically advanced and well-established.	The supply chain of recyled plastics is complex, leading to a lack of transparency about the origin and use of recycled materials.	Post-consumer plastic waste can be mixed with virgin materials to fulfil the property requirements for automotive applications.	New regulations on recycled plastics in the automotive industry could impact sector competitiveness outside the EU, unless the global adoption of recycled plastics becomes the standard.
Advanced discussions on regulations for recycled plastic materials are taking place in other industries.	The recycling rate of plastics from end-of-life vehicles is currently low (19%), as a significant amount of material is either incinerated or sent to landfills.	The EU production capacity for post-consumer recycled plastic could be expanded with relatively low financial investments.	New regulations on recycled plastics in the automotive industry could drive increased demand, leading to cross-sector sourcing competition and potential bottlenecks in recyled material supply.

benefits due to increasing consumer awareness on the plastic waste problem [driver 1]. More ambitious targets are deemed feasible in longer timeframe (e.g., 6–7 years after the adoption of the measure). This approach would also give sufficient time to industry progress with the development of chemical recycling technologies [driver 8] and consolidate emergent value chain partnership [driver 3].

4.1.3. Scope of the policy intervention

The third criterion relates to the scope of the policy intervention. Since a large variety of thermoplastics is used in passenger cars, considering the high volumes of post-consumer plastic waste [driver 4] in combination with the batch stability and related quality issues [barrier 10] and the property constraints in automotive applications [barrier 11], it was decided to avoid restricting the focus of the intervention to a specific polymer type. Accordingly, it is advised to apply the targets at a vehicle or type level. A target related to OEMs fleet could also be considered, but verification and monitoring procedures need to be further studied. Furthermore, it is noted that while the policy intervention should target a broad range of polymers, it could shift the balance in favour of those that are easier to recycle (e.g., PP) and used again in a vehicle with a closed loop [driver 7].

Reflecting these criteria, three policy options were developed, as further detailed in Table 3. These policy options aim to solve the current circularity market failures which limit the uptake of recycled plastics in the automotive sector. Stimulating the demand for recycled plastics may unlock investments and growth in the recycling sector, result in higher quantity and better quality of materials. The proposed options include both "non-binding" (e.g., soft tools such as voluntary pledges or economic incentives) and "binding" (e.g., definition of recycled content targets) regulatory measures.

These policy options must be carefully assessed through an impact assessment, which should complement the qualitative analysis, and should ideally be conducted concurrently. This involves quantitative modelling to evaluate how each policy option performs across supply/demand of recycled materials, environmental, and economic dimensions. While the qualitative analysis (encompassing drivers and barriers) is essential for defining the current state of play and high-level scope, timeline and ambition of policy options, the quantitative modelling allows to fine tune the specifics within defined policy options.

4.2. Contribution to circular economy research

This study contributes to scientific research on the drivers and barriers to the circular economy transition. This stream of research in the broader circular economy field originated recently, and is accelerating rapidly (Bauwens et al., 2020; Hondroyiannis et al., 2024; Ranta et al., 2018). Initial work on the subject effectively categorized the barriers and drivers conceptually, according to their cultural, regulatory, economic, technical nature, highlighting a broad gap of empirical research needed to better understand them in practice (de Jesus and Mendonça, 2018; Kirchherr et al., 2018). A growing body of empirical studies is now emerging to address this call to action (Chakori et al., 2021; Piila et al., 2022; Ranta et al., 2018). With this empirical study, we fill a fraction of the knowledge gap, by focusing on the supply chain of virgin and recycled plastic within the EU automotive sector. Some studies on the drivers and barriers to plastics circularity are presents, as well as separate studies on circularity drivers and barriers in the automotive sector (Agrawal et al., 2020; Bening et al., 2021; Chakori et al., 2021). However, studies that look at the drivers and barriers to plastic circularity specifically in the EU automotive sector are not yet present.

From a conceptual standpoint, our analysis takes place at a meso-level, focusing on a specific material supply chain, in a specific sector, in a specific geographical context. This meso-level focus, adopting the supply chain as unit of analysis, is relevant to address the limitations of both macro and micro-level empirical research on the barriers and drivers to the circular economy. Macro-level research, focusing on the economic system as a whole or on entire sectors might lack a sufficient level of granularity needed to support targeted actions and interventions related to a specific stakeholder group in a specific industry. For example, former research focusing on the barriers to circularity at a macro-level in the automotive sector has identified as barriers the higher cost of secondary material compared to primary, and the lack of suitable recycling technologies (Agrawal et al., 2020). In contrast, by further narrowing the focus to the meso-level of the plastic supply chain in automotive, our analysis is able to provide additional details needed to inform potential solutions, including: the influence of oil prices and waste batch stability upon the cost of secondary versus virgin plastic, and the prioritization of metal recovery over plastic recovery in the end-of-life phase of vehicles, which is in turn one of the key factors behind recycling challenges and material input quality. On the other hand, micro-level research, focusing on specific firms and their business model, often fails to capture important contextual factor and cross-organizational interactions that need to be understood and considered by policymaking interventions (Baldassarre and Calabretta, 2024; Nyffenegger et al., 2023, 2024; Baldassarre et al., 2019; Baldassarre, 2021). For example, former work identified as barriers to circularity for firms the financial viability and scalability of their circular business model and higher cost of labour and design to manufacture sustainable plastic products (Guldmann and Huulgaard, 2020; Vermunt et al., 2019). In contrast, by focusing our study at the supply chain

Table 3
EU policy options related to recycled plastics in context of the new end-of-life vehicle regulation proposal.

POLICY OPTION 1 Voluntary pledges for car manufacturers	POLICY OPTION 2 Mandatory information requirements	POLICY OPTION 3 Mandatory recycled content targets
Deploying a specific automotive sector pledge or voluntary circular "claims" for new vehicles placed on the market. This option may be implemented in conjunction with the adoption of the new regulation or with anticipation to foster virtuous circular behaviour by frontrunner companies. To prevent false or misleading claims or greenwashing, monitoring recycled material flows, and/or auditing vehicle manufacturers might be required.	Introducing a legally binding requirement that can be deployed quickly after the adoption of the legislation. Mandatory information would be required for the integration of recycled plastic grades (e.g., origins, total recycled, etc.) in each new vehicle put on the EU market.	Mandatory targets on minimum recycled plastic content aiming to generalize the uptake of recycled plastics by automotive suppliers and original equipment manufacturers. This option should consider a longer timeframe than the previous, to give the sector enought time to adapt to the legally binding instrument. Gradual targets can be proposed for smooth implementation and ensuring that the industry is able to reach the appropriate level of recycled plastics uptake. This option might create a "market pull" mechanism for recycled plastics, hence supporting the recycling business case. However, the feasibility of this ambitious policy measure should be carefully assessed to prevent market distortion and instability.

meso-level, we go beyond the firm-centric perspective, connecting the issue of circular business model viability to the wider problem of cross-organizational fragmentation and lack of economies of scale in the plastic recycling business.

Ultimately, our study shows how a meso-level focus on circularity barriers and drivers in the supply chain is relevant to gather both comprehensive and granular information based on multilateral stakeholder inputs, to derive more informed policy options. This relevance of this science for policy approach is mentioned in the EU *better regulation guidelines* (European Commission, 2021a), as well as in recent academic studies on industrial policy in the sustainability transition. Lindberg et al. (2019) have argued for the need of leveraging diverse perspectives of multiple stakeholders active in different supply chain positions to better inform EU policy mixes. More specifically related to EU circular economy policies, Cainelli et al. (2020) noted that in the ongoing transition from a waste management focus to a product life cycle focus, it is essential to study the implications of resource efficiency interventions on industry players. In turn, this requires more efforts on meso-level data collection efforts at the industry-policy nexus. Our study contributes to addressing this call to action by illustrating how such work may be conducted, focusing on the plastic supply chain, while parallel work is already emerging. For example, Bening et al. (2021) took a supply chain perspective in analysing barriers for plastic recycling in the packaging sector, while Paletta et al. (2019), building on case studies on plastic circularity barriers in the Italian context, argued that �“meso-scale analysis can represent a useful means supporting the creation of viable practical approaches towards achieving environmental and economic gains, especially in the European plastic industry” (p.1). In this vein, our work is functional to pinpoint a few key elements to be considered when conducting such analyses oriented towards concrete action. First, it is important to ground the analysis of the supply chain into former academic studies, as well as grey literature from industry and policymaking, which follows a faster publication cycle and might provide insight into contemporary developments not yet disseminated by scholars. Second, it is important to directly consult stakeholders while covering horizontally all the segments of the supply chain from the production of materials to the end-of-life phase of products. Third, visualizations of results and insights can be a powerful tool to engage with stakeholders and target audience of the study into meaningful conversations with practical relevance. Indeed, with this study we demonstrate the practical relevance of such meso-level analysis, by connecting the identified drivers and barriers to the development of policymaking options.

5. Conclusion and future research

This study is relevant to inform policy options in the context of the review of the *end-of-life vehicle directive* into a new regulation (European Commission, 2023b; European Parliament and Council, 2000). This study puts forward a supply chain analysis of plastics in the EU automotive sector, identifying cultural, regulatory, economic, and technical barriers to recycling. Future research may build on the limitations of this study to further support EU policymaking.

A first limitation relates to the analysis of environmental aspects. Such aspects are partially considered in the discussion of the identified barriers and drivers as they were not a core focus within the investigation. Future research may be conducted in this direction, especially with a view on the potential of plastic recycling in automotive to reduce environmental impacts related to pollution (e.g., land, water) and, importantly, energy consumption and carbon emissions. Increasing plastic recycling is essential to achieve decarbonisation (Cong et al., 2024; Enkvist and Klevnäs, 2018) and EU policymaking goals at the nexus between circular economy and net zero emission targets (European Commission, 2020a; European Parliament and Council, 2022).

A second limitation relates to the type of analysis performed, which was primarily qualitative, providing insight into the supply chain structure, processes, stakeholder interactions and types of material flows. On the quantitative side, the analysis performed in the context of this study included a partial quantification of some material flows and estimation of polymer mass of certain vehicle components.

While such quantification and estimation are useful for contextualizing the qualitative results, they remain preliminary and incomplete due to the omission of certain flows and the limited level of resolution provided. As part of the wider science for policy efforts—and outside the scope of this specific study—a quantitative analysis has been conducted to estimate the flows of plastic recycled at vehicle and fleet levels (Maury et al., 2023). Future research may build on this work by leveraging the qualitative insights to increase the resolution of material flow analyses of plastic in automotive, for example by disaggregating flows and on polymer and / or component basis (e.g. Kawecki et al., 2018).

Another direction for future research goes beyond the specific focus and limitations of this study, considering different materials and sectors. This is important to address knowledge gaps on circularity drivers and barriers and inform EU policies supporting new circular business models, in line with the forthcoming competitiveness compass shaped by the new European Commission (European Commission, 2025). A focus on carbon-intensive and critical raw materials is particularly relevant. Recent research suggests adopting a meso-level approach—using supply chains as the unit of analysis—for a systemic and detailed perspective (Baldassarre, 2025; Baldassarre et al., 2023; Axt et al., 2023). For carbon-intensive materials like aluminium, steel, chemicals, and concrete, identifying circularity drivers and barriers supports EU decarbonisation and net-zero goals, as recycling these materials emits far less carbon dioxide than primary production (Allwood et al., 2010; European Commission, 2020a). While some research exists (e.g., Pinto and Diemer, 2020), more systematic efforts aligned with this study's approach are needed. For critical raw materials, research is emerging but remains limited due to complex supply chains, confidentiality, and technological sensitivities (Baldassarre, 2025; Baldassarre et al., 2023; Buesa et al., 2025; Buesa et al., 2023; Buesa et al., 2024; Cimprich et al., 2022; European Commission, 2021b; Hartley et al., 2024). This is important for meeting the goals of the Critical Raw Materials Act, which emphasizes circularity as key to EU strategic autonomy and includes a 25% recycling target in supply chains for renewable energy, digital, and defence technologies (Carrara et al., 2023; Baldassarre and Carrara, 2025; European Parliament and Council, 2024; Jakimow et al., 2024).

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

CRediT authorship contribution statement

Brian Baldassarre: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thibaut Maury:** Writing – review & editing, Writing – original draft, Investigation. **Nacef Tazi:** Writing – review & editing, Investigation. **Fabrice Mathieux:** Project administration. **Serenella Sala:** Supervision.

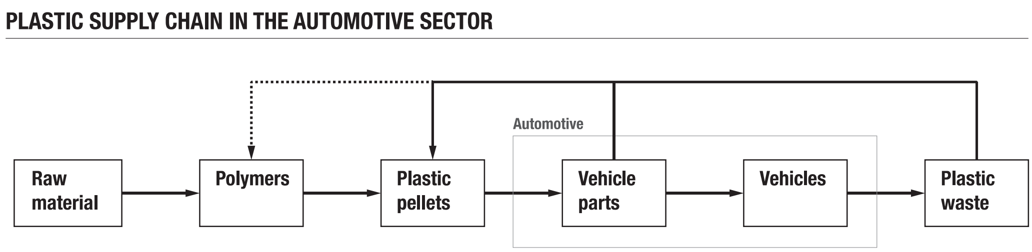
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The data collection was supported by the European Commission – Directorate General for Environment - Administrative Arrangement N ENV N° 070201/2020/840561/AA/ENV.B.3 “Support for Circular Economy Action Plan 2.0- Part 1: Short term actions” (2020- 2023).

Appendix A. – Interview guide



Introductory questions – overall supply chain structure

- Is the supply chain structure correct?
- How can it be improved and refined to increase the accuracy and level of detail?
- Which are the main stakeholder groups in the supply chain?
- Which are the main industrial processes in the supply chain?
- Which are the main factors to consider in relation to plastic recycling within automotive and across sectors?

Section 1**: Cultural drivers and barriers**

- How does the automotive sector embrace the use of recycled plastics in vehicle production?
- How do manufacturers integrate recycled plastics into their vehicles?
- How do organizational culture and trends affect the adoption of recycled plastics?
- Are stakeholders in the supply chain willing to share information to improve recycling practices?
- Do consumers, suppliers, and regulators influence how you use recycled plastics?
- How does collaboration across the supply chain impact the use of recycled plastics?
- How do cultural attitudes toward circularity affect the use of recycled plastics?
- What cultural shifts are needed to normalize the use of recycled content in the automotive sector?
- How can policies change cultural attitudes towards recycled plastics in vehicle manufacturing?
- How do market trends and branding pressure influence your decision to use recycled materials?

Section 2**: Regulatory drivers and barriers**

- How do EU regulations impact your ability to use recycled plastics in vehicles?
- What challenges do you face in verifying and tracking recycled plastic content?
- How do differing regulations across EU countries affect your operations?
- What gaps in current policies hinder plastic recycling in the automotive sector?
- How does global competition affect your compliance with EU recycling regulations?
- Should plastic waste regulations be harmonized globally? Why or why not?
- How could stricter EU policies promote the use of recycled plastics in vehicles?
- What barriers exist in implementing traceability for recycled materials?
- How do you balance regulatory compliance with staying competitive in the sector?
- How could harmonized standards for recycled plastic content improve industry practices?

Section 3**: Economic drivers and barriers**

- How do fluctuations in the cost of virgin vs. recycled plastics impact your decisions?
- What are the main business challenges in increasing recycled content in vehicle parts?
- How does supply chain fragmentation affect the availability and quality of recycled plastics?
- What role do new market entrants and partnerships play in improving recycling efforts?
- How do dismantling costs affect the economics of recovering plastics from end-of-life vehicles?
- How does your business model adapt to changes in the demand for recycled plastics?
- What steps can improve economies of scale for recycling in the automotive sector?
- How does material efficiency help reduce resource dependency in your operations?
- What investments or incentives are needed to scale up recycled plastic use in vehicles?
- How does blending recycled and virgin plastics affect cost and production decisions?

Section 4: **Technical drivers and barriers**

- What are the main technical challenges in increasing recycled plastics in vehicle components?
- Which polymers are commonly used in vehicle manufacturing, in which components and shared?
- How do their properties affect recycling of specific polymers, also considering contaminants or additives?
- Which polymers are easiest to recycle, and why?
- How do design constraints affect the recyclability of plastic components?
- Are there technologies that could improve the recycling process for automotive plastics?
- What trade-offs exist between material quality and using recycled content in vehicle components?
- How do additives, fillers, or hybrid materials impact recyclability and performance?
- How mature are recycling technologies, and what improvements are necessary?
- How does vehicle design impact the recyclability of plastic parts?

Appendix B. – Coding scheme

Table B1, Table B2

Table B1
Coding scheme for the identified barriers.

	#	Barrier	Selection of illustrative stakeholder inputs
Cultural	**1**	**Competitive advantage logic of industry players in relation to recycling best practices and their automotive applications.**	*The recipe of recycled plastic is almost always secret. We discuss with our suppliers only the properties of the material.* *Compounding recipes is our competitive differentiator. Our clients in automotive are very concerned with confidentiality.* *The software to simulate in advance the properties of the recycled output material is what we do differently from others.* *The details on how we deal with recycled material must be kept confidential.* *Our members are needed to preserve confidentiality concerning the details on how the implement recycled plastic material in their products.*
Cultural	**2**	**Divergent stakeholder views upon the responsibility to catalyse plastic circularity in the automotive sector.**	*It is difficult to deal with automotive as a client. It is a very traditionally minded sector, especially vehicle manufactures. Policy should drive the shift toward recycling plastic by making regulations.* *Automotive clients have very specific requirements. It is difficult to sell something new that deviates from the current approach. We manufacture components and do not have control over recycled content. That depends on our suppliers who produce the raw material. We are not concerned with the origin of recycled material, pre-consumer* vs. *post-consumer, because our clients do not demand this. They just ask for recycled plastic.* *Clients in automotive may struggle and be reluctant to use recycled plastic at scale. Most players know only their little part of the value chain. There is limited interest to share information with other parties as way to develop a comprehensive overview.* *The choice to use recycled plastics in an automotive firm must come from the CEO. If there is no solid business case this should be influenced by policy. Many of the costs of recycling plastic is charged to us. Vehicle manufacturers benefit but pay little of the costs involved.* *The solution on recycled plastic in vehicle components should come from the suppliers who manufacture those components. We focus our efforts on avoiding the use of crude oil, without making a distinction between pre-consumer and post-consumer recycled plastic.* *It is the vehicle and component manufacturers, who reach consumers and can use their influence on the market to set objectives linked to the integration of recycled plastic.* *The solution should come from policy makers. Policy targets must focus on post-consumer plastic because that is associated to more mass and a more waste.* *Players in the chemical industry are also responsible to ensure that plastic can be recycled, and more stringent policies should target them as well.* *We need policy action to influence the automotive industry.*
Regulatory	**3**	**Traceability and verification of recycled plastic embedded into vehicles imported from non-EU countries.**	*Our focus on design for recycling is only about facilitating the depollution of the vehicles, with limited organizational guidelines on plastics. There are no consistent industry standards and traceability schemes for plastic material and waste. We trust our suppliers. For us targets for recycled content are global and there is no difference between production in the EU, US and China.* *EU regulations on plastic recycling should be stricter, but there is problem with global competition.* *Regulations applied only to EU companies might reduce the competitiveness of the automotive EU sector on a global level. Stakeholders in the value chain do not have a clear picture on whether plastic is imported or sourced in the EU. Plastic parts produced in the EU are most likely assembled into cars in the EU. Suppliers manufacture regionally. There is not many exports of plastics parts in other regions of the world.* *We also need to consider the competition with non-EU manufacturers.* *Plastic waste is difficult to trace and regulate. There is limited transparency regarding provenance and use of recycled content embedded into products, including vehicles. New regulations on recycled plastic in automotive might affect competitiveness of the sector outside the EU, unless the use of recycled plastics becomes the norm globally.* *Focusing targets on plastic material and plastic and plastic waste only produced and dismissed in the EU would not work. This would not be WTO compatible. But creates a lot of traceability challenges.*

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Table B1 (*continued*)

	#	Barrier	Selection of illustrative stakeholder inputs
			Blending recycled content with virgin material allows to meet technical requirements of different components bur creates challenges in the traceability of recycled content.
Regulatory	**4**	**Differences in plastic waste management regulations across EU countries.**	*At high level, within EU countries that are doing good, most of the plastic waste is still burned, about 50%. Follows recycling, and very little landfill. In countries that are not doing so good there is mostly landfill, about 60%, follows burning and very little recycling.* *19% are the recycling rates according to some estimates. Incineration contributes to greenhouse emissions, so that must be increased.* *Different regulations across countries affect how waste management is done. Spain is against incineration, even with energy recovery, preferring to send waste to landfill even if landfilling is lower in the waste management hierarchy.* *The infrastructure to recycle waste differs greatly country by country in the EU.*
Economic	**5**	**Fluctuations in the cost of virgin and recycled plastic.**	*More R&D is needed to decrease the cost of using recycled material. Recycled PET is more expensive than the primary.* *Using recycled PET in the textiles of the interior of the cars is more expensive.* *Competitiveness of the recycled plastic on the market is highly dependent on the oil price, which fluctuates. Also, oil price is assessed at the moment of the design of the car and not when the vehicle is manufactured. The cost of recycled material is also influenced by the testing needed to assess its performance properties. Virgin material composition is constant; therefore, testing is needed only once. Secondary material composition changes frequently, requiring more frequent testing. We do the baseline testing, but some clients require more and with more frequency, and this affects the cost of the product we sell them. We have to charge an additional fee.* *Recycled material needs to be tested before we can use it. This makes it more expensive.* *There is a high degree of variability in the cost of plastic material. The cost of virgin material fluctuates with oil prices. The cost of secondary material depends on many, often local, factors.* *Our recycled PP is definitely cheaper than virgin PP. The price of virgin PP is influenced by oil prices and also by other factors.* *The only driver behind the demand of recycled plastic is the price of virgin plastic.* *Besides investment, recycled plastic should probably become more expensive to support the business case.*
Economic	**6**	**Prioritization of metal recovery over plastic recovery in the vehicle end-of-life phase.**	*The leader of the business in the dismantling is companies that want to recover metal. The car is crushed altogether, then metal is extracted and then you are left with a stream of mixed plastic difficult to separate and so with low commercial value, making it more convenient to use more expensive virgin material instead of investing in know-how and equipment for separation. If plastic makers would be the leader of the business, parts would be taken out before crushing the car, which would make it a lot easier to recover plastic that is less mixed. But we are small and it is not so easy for us to change the current ways.* *The problem is how the vehicle shredders operate. They focus on metal recovery because it is more economically attractive and this is their core business. Shredding machines are not very sophisticated and in 10 s they grind the car, resulting in a very diverse mix of plastic that is then difficult to separate. To convince shredders to change this way of doing, a business for plastic recycling should be provided, which needs to be based on big volumes.* *The current approach focuses mostly on decontamination of the vehicle at the end-of-life, removing toxic and liquids before shredding. It does not focus on plastic recovery. Metal recovery is driven by business.* *After shredding iron is separated with magnets.* *A vehicle is grinded altogether after depollution. Metal recovery is easy. Plastic is a different challenge.*
Economic	**7**	**Supply chain fragmentation and lack of economies of scale in the plastic recycling business.**	*The mechanical recycling business is fragmented. There are many stakeholders. Some do separation, other regrind, some compound (3–4% high quality recycling), etc. This fragmentation creates challenges in having a constant flow of secondary material that is homogeneous and clean enough to be recycled easily. We are a small business and there is a limit to the output we can produce. In general, in the recycling business there are many small companies that are specialized into different steps of the process. Initiating and scaling up a recycling business that is economically viable in the long run requires substantial up-front investments. Non many companies can afford it, or are willing to take such risk.* *The machines for compounding recycled plastic and virgin plastic are different.* *Suppliers of virgin plastic material and suppliers of recycled plastic material are often different companies with different expertise. A paradigm shift in the value chain is needed.* *What is missing in order to make current best practices the norm, is mandatory targets which provide the certainty needed by recyclers to scale up existing facilities and invest into new ones.* *Many firms say that recycling post-consumer plastic is unfeasible because they are not big enough and lack the economies of scale to make it profitable. The key to our success is being big enough to make the economics work. In this way we are able to integrate new competences in the supply chain of secondary material. For example, we are part of a bigger group that collects waste. We get involved in the dismantling of vehicles to source material. We acquired a business that produces plastic components and source waste from them. This allows us to keep supply quantity and quality under control. A second key success factor is the acquisition of companies that produce plastic components using recycled material, and source from them the pre-consumer plastic waste to create a closed loop.* *To support our business, we need a constant flow of plastic waste. Otherwise profit margins become extremely narrow.* *Our expertise includes CAE/Moldflow modeling software that producers of virgin plastic may not be able to use. They are essential especially for the design and prototyping and manufacturing of technical and safety components made of recycled plastic.*
Economic	**8**	**High cost of dismantling vehicle components before shredding**	*Dismantling of cars to recover homogenous plastic parts is complex. This problem is not there with packaging.*

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Table B1 (*continued*)

	#	Barrier	Selection of illustrative stakeholder inputs
			If there are specific parts that have a big enough mass that justifies having them removed in the dismantling process, this should be done and have a closed loop for high quality recycling. But for recyclers, doing so it does not make sense because it is expensive and might not fit with their processes. So closed loop is really not possible. *Dismantling plastic part from cars for recycling is very expensive. It takes a lot of time to dismantle. And then still, you need to transport and shred. It needs to be made compact before transport. Long story short: it costs too much. It could be done for the biggest plastic parts only, but even for them the business case is very difficult. Who is going to pay for it? But if there is an economic incentive, for example EU targets and consequent redistribution of costs across automotive stakeholders, then it might become economically viable. For sure it is technically feasible for big parts like bumpers, fuel and water tanks.* *Dismantling costs are around 40 Euros per end-of-life vehicle.* *Dismantling is too expensive. Some components in good conditions are extracted for reuse, for example the doors, and shipped to non-EU countries, for example to North Africa and the Middle East.* *We need modular design to aid dismantling, a narrower spectrum of materials used, and lighter components.*
Economic	**9**	**Limited availability of high-quality pre-consumer plastic waste.**	*Secondary raw material needs to be available in sufficient quantity and quality. There could be shortages due to inter-sectoral competition to get it, leading to an artificial price increase. It is difficult for tier 1 suppliers to know how much quantity of recycled plastic will be ordered by our OEM clients.* *Mainstream adoption of PET from recycled plastic bottles in the textiles of the interior of vehicles, may lead to shortages and competition between OEMs to source it.* *The higher the demand for a secondary material, the more difficult and expensive it becomes for manufacturers to source it. Who moves first gets the material that easier and cheaper to recycle, which is clean and with a relatively lower diversity mix.* *We could quickly increase our production volumes, but constant supply of secondary material sufficiently homogeneous remains a challenge.* *Pre-consumer plastic waste is suitable for recycling. However, very often, "clean" pre-consumer plastic waste is mixed with post-consumer waste, then becoming difficult to separate and recycle.* *Closed loop in the automotive sector is not realistic. Waste management is cross-sectoral. Plastic shreds from different sectors are mixed. It is very difficult to make plastic waste from the automotive sector flow back into the automotive sector. And also tracing this would be impossible.* *There are no shredders in Europe that shred only ELV. It is always mixed. Pre-consumer and post-consumer plastic waste are often mixed.*
Technical	**10**	**Low-quality of post-consumer plastic waste.**	*Aged plastic material with degraded properties rarely complies with safety regulations. The majority of plastic waste material comes from post-consumer sources, difficult to recycle because of uncertainties on composition, batch to batch stability, potential presence of impurities or even hazardous/restricted substances, age, etc.* *Recycling post-consumer plastic requires depollution, separation of different plastic types by density or electrostatic sorting, re-compounding or new extrusion which is complex in case of high-quality recycled polymer grades.* *Volatile organic compounds, contaminants and additives are one of the problems for the recycling of post-consumer plastic waste into pellets of sufficient quality.* *Before recycling chlorinated rubber must be separated from non-chlorinated rubber. Chlorinated rubber is used to increase thermal resistance, but it cannot be recycled. Another problem is glue. It hinders recyclability.* *Automotive shreds are more difficult to recycled because they contain a lot of PVC, which contains a lot of contaminant additives. WEEE plastic waste is much "cleaner" although it is very difficult to separate.* *It is the level of contamination that makes the recycling efficiency of ELV plastic lower than other sectors. Another reason is the high number of polymer types and grades in ELV. PVC is also a contaminant in plastic sorting and recycling.*
Technical	**11**	**Property constraints in the application of recycled plastic in new vehicle components.**	*Using recycled plastic in the interior of the vehicle can compromise the aesthetics and odor.* *Vehicle components need to satisfy strict requirements in terms of mechanical and thermal resistance.* *We can use recycled plastic only in a few components. Our OEM clients demand a huge diversity in virgin and recycled plastic grades, shapes, and cost ranges significantly. The client is very attentive to aesthetics as well.* *Under the hood you need thermal properties. For that, copolymers are not suitable, but only homopolymers.* *Components in ABS and PC are more sophisticated and often require virgin material. Few polymers are suitable for recycling, mostly PP when it does not contain additives and fillers. PA on the other hand contains glass fibers so if you recycle it many times you lose mechanical properties. There are 250 grades of PA, and the production process is optimized for each one of them.* *Vehicle components have narrow material specifications, multiple process steps, which require long term availability of selected materials, which need to have a long lifetime in the vehicle, thus need to satisfy thermal and safety constraints.* *Requirements of plastic components differ brand by brand and model by model. There is no single solution that can fit all.* *The requirements of our clients in terms of material choices and related testing are very different.*
Technical	**12**	**New composite and advanced materials for automotive applications containing fibres which cannot be recycled.**	*Some manufacturers make use of coconut or cellulose fibers that we cannot recycle. These fibers are blended into plastics like glue they make it unrecyclable. They are used because they are light. But also because vehicle manufactures can claim that they are sustainable. This is*

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Table B1 (*continued*)

	#	Barrier	Selection of illustrative stakeholder inputs
			greenwashing. *Some clients ask us to embed fibers in the components we supply.* *Natural fibers can be used to increase the resistance of plastic components while keeping them light. This allows to have a lighter vehicle, resulting in less carbon emission in the use phase.* *We are going to focus more on sustainable and composite materials, for example using bioplastics, natural fibers as fillers and PA coming from biobased sources and tall oil.*
Technical	**13**	**Material losses in the collection and recycling of plastic waste.**	*10% losses is linked to our plastic recycling and compounding processes.* *There are losses in a recycling plant.* *There is a huge gap in the plastic that is supposed to enter shredders and the plastic that comes out of them.* *The question is: what is the efficiency rate of a shredder?*
Technical	**14**	**Mismatch between innovation processes and length of vehicle life cycle.**	*Safety regulations on plastic materials that can or cannot be used in vehicles change over time (for example on VOCs, flame retardants) change faster than the life-cycle of the vehicle.* *There is a gap of 15–20 years between the design and production of components and their end-of-life. In this timeframe regulations on plastics materials change. We are reluctant make contracts with our suppliers that are longer than 7 years because in that timeframe regulations on materials and production technologies might change, which also greatly affects the costs of the recycled materials. We are struggling to maintain the same amount of recycled content because of innovation with some components. Some of the new components require virgin material, not recycled material. We are not ready to try implementing recycled material in new components.* *Aged plastic material with degraded properties rarely complies with safety regulations.* *Timeframe between design and end of life make recycling a massive challenge. Also, recyclers and vehicle manufacturers need to collaborate in the design phase, which is not obvious. They don't have time to do so.* *Timing for introducing regulations is an issue. Vehicle manufactures need time to adjust with regards to the production of new models. Plus, the stock of electric vehicles is increasing. This may have a lasting effect on recycled plastic. There might be less recycled plastic because of the transition to EV, at least in the short term.* *Design for recycling interventions done now will only have an effect in 15 years from now. This is the average life of the vehicle. To make it more difficult we are switching to electric vehicles, and so the type of plastic components in cars is changing. For example, the fuel tank.*
Technical	**15**	**Potential rebound effects of plastic recycling on carbon emissions.**	*More recycled plastic mass in the vehicle will result in higher carbon emissions in the use phase of the vehicle. Plus, sourcing secondary plastic material entails transportation with related carbon emissions.* *Recycled components may need ribs to increase mechanical resistance. This can increase the weight of the vehicle posing a question on whether we should prioritize plastic circularity or carbon emissions.* *There is a tradeoff btw lightweight* vs. *single-material components. Single-material components are easier to recycle but lightweight ones result in lower emissions in the use phase of the vehicle.* *Energy consumption for mechanical recycling is a lot and it needs to be factored into environmental impact assessment.* *Recycling needs green energy to be fully sustainable.* *Carbon costs of recycling are often not considered.*

Table B2
Coding scheme for the identified drivers.

	#	Driver	Selection of illustrative stakeholder inputs
Cultural	**1**	**Increasing consumer awareness around the plastic waste problem.**	*Global trends require us to adopt environmental strategies to reduce carbon emissions and waste. Consumer awareness of the plastic problem is also an incentive of using recycled material, but the return on investment is for us difficult to quantify.* *We want to integrate recycled plastic content into our vehicles because consumers are responsive to this. There is a business case behind using recycled plastic. We can state that our cars contain recycled content and this impacts our brand value. Most vehicle manufactures now want to use recycled content. It is becoming a competitive issue.* *By 2025, we aim to have 25% of recycled and biobased plastic in our cars.* *Consumers are more and more aware of sustainability issues. They are sensitive to plastic waste coming from bottles, packaging and so on. But they might be less sensitive to recycled plastic in cars, because of the loose connection with the plastic waste problem and because of the high relative cost of the car. There are probably more important factors driving purchase decisions, such as price, design, etc.* *People are becoming more aware of the plastic waste problem and this put pressure on companies.* *Our sustainability strategy is the main driver for using recycled content.* *Our clients demand components containing recycled content. Recycled content appears as an item within the list of requirements of their purchase orders.*
Regulatory	**2**	**Emergence of policy targets for plastic recycling and complementary sustainability regulations.**	*More stringent policies on recycled plastic might force demand of recycled plastic and fuel progress with recycling technologies.* *Regulations can support our business and speed-up the uptake of recycled plastic in industry.* *General specification for recycled PP, based on the activities of the Alliance, on ISO 22,628 on Recyclability/Recoverability rate, and on CEN-EN 45,557 recycled material content in*

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Table B2 (*continued*)

	#	Driver	Selection of illustrative stakeholder inputs
			energy related product, would help standardize the output, ensure its constant quality and make its application easier. *Carbon pricing or option to give an economic value to recycled plastics, for example through the […] scheme in France, could be a game changer.* *There is currently no certification for mechanical recycling. There are however certifications for biobased materials. Such schemes could be then replicated for mechanical recycling and we are investigating this.* *Targets should be technology and material neutral. It is urgent to deal with post-consumer plastic waste. But if regulations boost demand of recycled plastic, can supply follow? Investment is needed.* *Post-consumer plastic mostly comes from packaging because there are already regulations in place for packaging, which results in better sorting systems and therefore more recycling. In automotive this is not in place yet.*
Economic	**3**	**New players and supply chain partnerships aiming to increase production and adoption of recycled plastics in the automotive sector.**	*We have been working with this vehicle manufacturer for a long time, we understand their problems with using recycled plastic and try to deliver the solutions they need. Companies in the recycling business are specialized in doing different, complementary things, shaping the market.* *We have been sourcing recycled plastic from our trusted suppliers for years. We trust them and the product they deliver. This was essential to increase the recycled content in our cars.* *New players are entering the recycling business. The historical players already acquired expertise with separation. New entrants, such as Borealis and Total, are focusing on different things, mostly chemical recycling.* *More and more companies are specializing in recycling.* *Our company wants to become a loyal partner of manufacturers. We are doing partnerships in the field of chemical recycling.* *Collaboration with research institutes is essential to get chemical recycling up and running. Collaboration with trust is needed.*
Economic	**4**	**High volumes of post-consumer plastic waste from different sectors.**	*Currently mostly pre-consumer waste is used in recycling. But 90% of plastic waste is unused post-consumer waste, resulting in a big market opportunity.* *The estimations derived from the mass and flows model will give you an idea of the huge size of the stock embedded in end-of-life vehicles but also waste of electrical and electronic equipment.* *PET fibers are now largely imported from China. It would be nice to instead use PET fibers from the 60% of plastic bottles which are not recycled today in the EU. Demand for PET is there. Recycled material can compete with virgin material.* *The large amount of post-consumer plastic waste from other sectors offers the opportunity of inter-sectorial exchange with the automotive sector. More supply of recycled content will create more demand. Suppliers in the automotive sector will be able to source the inputs they need from recyclers, who in turn can source their inputs from other sectors in an open loop.* *Post-consumer plastic waste and recycling varies greatly sector by sector, with packaging in the lead.*
Technical	**5**	**Blending recycled and virgin pellets to meet the material requirements of new vehicle components.**	*"Hybrid" material blends recycled content, ranging between 30 and 90%, with virgin material. These are also called booster and offer the opportunity to meet technical requirements.* *Boosters and fillers are chemicals injected into post-consumer material during the compounding process, as a way to make its mechanical and thermal properties suitable for automotive application. The quantity of the booster or filler is usually around 80%. They represent a good, market-ready alternative to chemical recycling. However, they cannot compensate for volatile organic compounds and odors. Blending recycled content with other stones or oyster shells can be done to achieve cool colors and textures with recycled plastic in the interior of the car.* *Mixing of virgin with recycled polymers is possible to meet automotive component requirements.* *The mass of plastic containing recycled content is different from the mass of actual recycled content. Basically, what we call recycled plastic contains "some" recycled material, usually 25%.*
Technical	**6**	**Maturity of mechanical recycling technologies.**	*We use software to simulate up-front the properties of the output recycled material, based on the inputs that we are going to use. This allows to cut time and costs.* *Material separation technology from the 80s.* *Density separation. 30Tons per hour of material can be separated.* *Design and manufacturing of some safety components made of plastics entails prototyping based on software testing and simulations, such as CAE and Moldflow, which allow to assess the quality of the output material. However, numeric data for such simulations is often missing.* *We use software to test the properties of recycled output.* *EU production capacity of recycled plastic might be increased with rather limited financial investments.*
Technical	**7**	**Adoption of polymers that are easier to recycle due to the transition to electric vehicles.**	*When PP is not mixed with fillers and additives, it can be relatively easy and inexpensive to recycle.* *Recycled PP is not expensive. We focus on it.* *The engine of electric vehicles heats up less compared to a combustion engine. This will make it possible to use more PP for under the hood components, including the cooling circuits currently made of PA to withstand 110°. In electric vehicles they can be done with PP, which can withstand 80°. In the future, with the diffusion of electric vehicles, we expect that the use of PP will also increase, along with the potential to use recycled material, since PP is the easiest plastic to recycle. For basic parts of the vehicle that are hidden and have no technical*

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Table B2 (*continued*)

	#	Driver	Selection of illustrative stakeholder inputs
			requirements, usually 6% of the car, PP can be used. Its recycling can be relatively easy and inexpensive. *We mainly do PP, about 50% of our total volumes. PP is the easiest polymer to recycled because its density is below 1, and therefore it is easy to sort out from the other plastics inside the water tank.*
Technical	**8**	**Progress with chemical recycling technology.**	*Chemical recycling could be the solution to make recycling simple.* *Chemical recycling is promising. But maturity is still low. 10 years might still be needed. Validation is needed at the material level. Also, the environmental footprint of uptaking chemical recycling is uncertain. It should be assessed carefully before moving forward with it. It is not a substitute of mechanical recycling but rather complementary to it for different needs and possibly new applications.* *There is still a lot of validation to do with chemical recycling, at the material level and at the component level. But some companies are speeding up, which could make this technology market ready in a few years from now.* *Chemical recycling, through depolymerization, of PET and PUR is closest to market readiness. This is realistic in the short term. With PUR the main problem is sorting of different types of PUR. Chemical recycling does not allow to completely skip the separation step, as it was hoped initially. In general, for most polymers a lot of R&D is still needed, to make this technology technically ready and also less expensive.* *In principle anything can be recycled chemically, but ad-hoc processes need to be designed and they easily become very expensive. With PUR there is selective depolymerization. This could be used for car seats. But seats are very difficult to take out of the car and then they need to be skinned, removing the outer layer. Chemical recycling of PUR only works when it is clean. We want to focus our efforts on chemical recycling for the fraction of waste that cannot be dealt with mechanical recycling.* *You always need separation before chemical recycling.* *Chemical recycling is not a single technology. There are many types of chemical recycling and they all need to be developed. Sorting is still needed. But the companies involved in it are not so keen to share the specifics. Chemical recycling is currently still at pilot scale. It needs green energy to be fully sustainable.*

Data availability

The authors do not have permission to share data.

References

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for achieving a 50% cut in industrial carbon emissions by 2050. Environ. Sci. Technol. 44 (6), 1888–1894. https://doi.org/10.1021/es902909k.

Agrawal, R., Wankhede, V.A., Kumar, A., Luthra, S., 2020. Analysing the roadblocks of circular economy adoption in the automobile sector: reducing waste and environmental perspectives. Bus. Strategy. Environ. 30 (2), 1051–1066. https://doi.org/10.1002/bse.2669.

Agyemang, M., Kusi-Sarpong, S., Khan, S.A., Mani, V., Rehman, S.T., Kusi-Sarpong, H., 2019. Drivers and barriers to circular economy implementation: an explorative study in Pakistan's automobile industry. Manag. Decis. 57 (4), 971–994. https://doi.org/10.1108/MD-11-2018-1178.

Arcipowska, A., Baldassarre, B., Blanco Perez, S., Polverini, D., Cabrera, M., 2024. Role of solar PV in net-zero growth: an analysis of international manufacturers and policies. Prog. Photovolt.: Res. Appl. 1–16. https://doi.org/10.1002/pip.3797.

Antonopoulos, I., Faraca, G., Tonini, D., 2021. Recycling of post-consumer plastic packaging waste in EU: process efficiencies, material flows, and barriers. Waste Manag. 126, 694–705. https://doi.org/10.1016/j.wasman.2021.04.002.

Axt, M., Baldassarre, B., Kirchherr, J., Vestergaard, J., 2023. Circular economy in critical value chains: the case of hydrogen electrolysers and fuel cells. Aalto University Publication Series, pp. 77–83. https://doi.org/10.13140/RG.2.2.36270.48961.

Baldassarre, B., 2021. From Problem to Solution: A Few Stories About Design and Business for Sustainable Development. In Doctoral diessertation. Delft University of Technology. https://doi.org/10.4233/uuid:69d868ef-33d0-4abf-a33c-dac9a0577e78.

Baldassarre, B., Micciché, N., 2014. Into the grey: towards successful implementation and effective evaluation of "Design for Development" projects. Design, Development & Research Conference, pp. 97–98.

Baldassarre, B., Bocken, N., Calabretta, G., Diehl, J., Keskin, D., 2019. Track 4.f Introduction: Strategic Design of Sustainable Business Models, 2. Academy for Design Innovation Management, pp. 803–806. https://doi.org/10.33114/adim.2019.4f.

Baldassarre, B., Buesa, A., Albizzati, P.F., Jakimow, M., Saveyn, H., Carrara, S., 2023. Analysis of Circular Economy Research and Innovation (R&I) intensity for critical products in the supply chains of strategic technologies. Publications Office of the European Union. https://doi.org/10.2760/582527.

Baldassarre, B., Buesa, A., Albizzati, P.F., Jakimow, M., Tercero, L., Stijepic, D., 2023. Titanium metal circularity in the EU Status quo and future potential. IRTC 2023 – Raw Materials for a Sustainable Future. https://doi.org/10.13140/RG.2.2.12128.97286.

Baldassarre, B., Calabretta, G., 2024. Why circular business models fail and what to do about it: a preliminary framework and lessons learned from a case in the European Union (Eu). Circ. Econ. Sust. 4, 123–148. https://doi.org/10.1007/s43615-023-00279-w.

Baldassarre, B., Carrara, S., 2025. Critical raw materials, circular economy, sustainable development: EU policy reflections for future research and innovation. Resour. Conserv. Recycl. 215, 108060. https://doi.org/10.1016/j.resconrec.2024.108060.

Baldassarre, B., Maury, T., Mathieux, F., Garbarino, E., Antonopoulos, I., Sala, S., 2022. Drivers and barriers to the circular economy transition: the case of recycled plastics in the automotive sector in the European Union. Procedia CIRP. 105, 37–42. https://doi.org/10.1016/j.procir.2022.02.007.

Baldassarre, B., 2025. Circular economy for resource security in the European Union (EU): case study, research framework, and future directions. Ecol. Econ. 227, 108345. https://doi.org/10.1016/j.ecolecon.2024.108345.

Baldassarre, B., Saveyn, H., 2023. A systematic analysis of EU publications on the Circular Economy. Publications Office of the European Union. https://doi.org/10.2760/36203.

Bauwens, T., Hekkert, M., Kirchherr, J., 2020. Circular futures: what will they look like? Ecol. Econ. 175 (May), 106703. https://doi.org/10.1016/j.ecolecon.2020.106703.

Belmonte-Ureña, L.J., Plaza-Úbeda, J.A., Vazquez-Brust, D., Yakovleva, N., 2021. Circular economy, degrowth and green growth as pathways for research on sustainable development goals: a global analysis and future agenda. Ecol. Econ. 185 (August 2020). https://doi.org/10.1016/j.ecolecon.2021.107050.

Bening, C.R., Pruess, J.T., Blum, N.U., 2021. Towards a circular plastics economy: interacting barriers and contested solutions for flexible packaging recycling. J. Clean. Prod. 302, 126966. https://doi.org/10.1016/j.jclepro.2021.126966.

Bilal, M., Khan, K.I.A., Thaheem, M.J., Nasir, A.R., 2020. Current state and barriers to the circular economy in the building sector: towards a mitigation framework. J. Clean. Prod. 276, 123250. https://doi.org/10.1016/j.jclepro.2020.123250.

Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. J. Ind. Ecol. 21 (3), 603–614. https://doi.org/10.1111/jiec.12603.

Brown, P., Bocken, N., Balkenende, R., 2019. Why do companies pursue collaborative circular oriented innovation? Sustainability. 11 (3), 635. https://doi.org/10.3390/su11030635.

Buesa, A., Albizzati, P., Garbarino, E., Saveyn, H., Baldassarre, B., 2023. Circular economy in EU critical value chains: the case of titanium metal in defence and civil aviation. In: Niinimäki, K., Cura, K. (Eds.), Product Lifetimes And the Environment 2023. Aalto University Publication Series, pp. 149–154. https://doi.org/10.13140/RG.2.2.11104.66566.

Buesa, A., Piñero, P., Pedauga, L., Rueda-Cantuche, J.M., Baldassarre, B., 2024. Can circularity in Titanium metal improve EU strategic autonomy? Scenario modelling with heterogeneous data. JRC Working Papers in Economics and Finance, 2024/06. https://publications.jrc.ec.europa.eu/repository/handle/JRC139576.

Buesa, A., Georgitzikis, K., Jakimow, M., Piñero, P., Maury, T., Latunussa, C., Pedauga, L., Samokhvalov, V., Baldassarre, B., Mathieux, F., Rueda-Cantuche, J.M., Stijepic, D., Reys, A., Bilous, A., Notom, P., Tercero, L.A., 2025. Titanium metal in the EU : Strategic relevance and circularity potential. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC137082.

Cainelli, G., D'Amato, A., Mazzanti, M., 2020. Resource efficient eco-innovations for a circular economy: evidence from EU firms. Res. Policy. 49 (1), 103827. https://doi.org/10.1016/j.respol.2019.103827.

Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, A., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Christou, M., 2023. Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU: A foresight Study. Publications Office of the European Union. https://doi.org/10.2760/334074.

Chakori, S., Aziz, A.A., Smith, C., Dargusch, P., 2021. Untangling the underlying drivers of the use of single-use food packaging. Ecol. Econ. 185 (March), 107063. https://doi.org/10.1016/j.ecolecon.2021.107063.

Cimprich, A., Young, S.B., Schrijvers, D., Ku, A.Y., Hagelüken, C., Christmann, P., Eggert, R., Habib, K., Hirohata, A., Hurd, A.J., Lee, M.H., Peck, D., Petavratzi, E., Tercero Espinoza, L.A., Wäger, P., Hool, A., 2022. The role of industrial actors in the circular economy for critical raw materials: a framework with case studies across a range of industries. Miner. Econ. https://doi.org/10.1007/s13563-022-00304-8, 0123456789.

Circle Economy Foundation. (2024). The circularity gap report 2024: a circular economy to live within the safe limits of the planet.

Circular Plastic Alliance. (2020). Work plan on state of play collection and sorting - automotive working group.

Circular Plastic Alliance. (2021a). Guidance on Waste Definitions (final draft).

Circular Plastic Alliance. (2021b). Roadmap to 10 Mt recycled content by 2025 (final draft).

Cong, R., Fujiyama, A., Matsumoto, T., 2024. Optimal plastic recycling system and technology development could accelerate decarbonization: a case study from Japan. Waste Manag. 175, 110–120.

Deloitte Sustainability. (2017). Blueprint for plastics packaging waste: quality sorting & recycling - final report. https://www2.deloitte.com/content/dam/Deloitte/my/Documents/risk/my-risk-blueprint-plastics-packaging-waste-2017.pdf.

de Jesus, A., Mendonça, S., 2018. Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. Ecol. Econ. 145 (July), 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001.

Diaz Lopez, F.J., Bastein, T., Tukker, A., 2019. Business model innovation for resource-efficiency, circularity and cleaner production: what 143 cases tell us. Ecol. Econ. 155 (March 2017), 20–35. https://doi.org/10.1016/j.ecolecon.2018.03.009.

Ellen MacArthur Foundation. (2013). Towards the circular economy (Vol. 2). https://doi.org/10.1007/b116400.

Emilsson, E., & Dahllöf, L. (2019). Plastics in passenger cars: a comparison over types and time. https://doi.org/10.13140/RG.2.2.16313.93280.

Enkvist, P.A., Klevnäs, P., 2018. The circular economy—a powerful force for climate mitigation. Material Economics: Stockholm, Sweden.

Esposito, M., Tse, T., Soufani, K., 2018. Introducing a circular economy: new thinking with new managerial and policy implications. Calif. Manage. Rev. 60 (3), 5–19. https://doi.org/10.1177/0008125618764691.

European Commission, 2015. Closing the Loop - An EU action Plan for the Circular Economy. Publications Office of the European Union.

European Commission, 2019. The European Green Deal. Publications Office of the European Union.

European Commission, 2020a. Circular Economy Action Plan. Publications Office of the European Union.

European Commission, 2020b. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Implementation of Directive 2000/53/EC on End-of-Life Vehicles for the Period 2014-2017. Publications Office of the European Union.

European Commission, 2021a. Better regulation guidelines. Publications Office of the European Union. https://doi.org/10.1057/9780230321359_10.

European Commission, 2021b. Updating the 2020 New Industrial Strategy: Building a stronger Single Market For Europe's recovery. Publications Office of the European Union.

European Commission, 2023b. Proposal for a regulation of the European parliament and of the council on circularity requirements for vehicle design and on management of end-of-life vehicles, amending Regulations (EU) 2018/858 and 2019/1020 and repealing Directives 2000/53/EC and 2005. Official Journal of the European Union 0284, 1–23.

European Commission, 2025. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A Competitiveness Compass for the EU. Publications Office of the European Union.

European Parliament and Council, 2000. Directive 2000/53/EC of the European parliament and of the council of 18 September2000 on end-of life vehicles. Off. J. Euro. Union L (269), 34–42.

European Parliament and Council, 2008. Directive 2008/98/EC of the European parliament and of the council of 19 November 2008 on waste and repealing certain Directives. Off. J. Euro. Union L312, 1–59.

European Parliament and Council, 2022. Directive (EU) 2022/2464 of the European parliament and of the council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting (Text with EEA relevance). Off. J. Euro. Union L 322, 15–80.

European Parliament and Council, 2024. Regulation (EU) 2024/1252 of the European parliament and of the council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/17. Off. J. Euro. Union March, 1–67.

Fereday, J., Muir-Cochrane, E., 2006. Demonstrating rigor using thematic analysis: a hybrid approach of inductive and deductive coding and theme development. Int. J. Qual. Methods 5 (1), 80–92. https://doi.org/10.1177/160940690600500107.

Gazeau, B., Minunno, R., Zaman, A., Shaikh, F., 2024. Elevating recycling standards: global requirements for plastic traceability and quality testing. Sustainability. 16 (12), 5122.

Guimarães, Y.M., Eustachio, J.H.P.P., Filho, W.L., Martinez, L.F., do Valle, M.R., Caldana, A.C.F., 2022. Drivers and barriers in sustainable supply chains: the case of the Brazilian coffee industry. Sustain. Prod. Consum. 34, 42–54. https://doi.org/10.1016/j.spc.2022.08.031.

Guldmann, E., Huulgaard, R.D., 2020. Barriers to circular business model innovation: a multiple-case study. J. Clean. Prod. 243, 118160. https://doi.org/10.1016/j.jclepro.2019.118160.

Hart, J., Adams, K., Giesekam, J., Tingley, D.D., Pomponi, F., 2019. Barriers and drivers in a circular economy: the case of the built environment. Procedia CIRP. 80, 619–624. https://doi.org/10.1016/j.procir.2018.12.015.

Hartley, K., Baldassarre, B., Kirchherr, J., 2024. Circular economy as crisis response : a primer. J. Clean. Prod. 434 (October 2023), 140140. https://doi.org/10.1016/j.jclepro.2023.140140.

Hondroyiannis, G., Sardianou, E., Nikou, V., Evangelinos, K., Nikolaou, I., 2024. Circular economy and macroeconomic performance: evidence across 28 European countries. Ecol. Econ. 215 (October 2023), 108002. https://doi.org/10.1016/j.ecolecon.2023.108002.

Jakimow, M., Samokhvalov, V., Baldassarre, B., 2024. Achieving European Union strategic autonomy : circularity in critical raw materials value chains. Int. Affairs 100 (4), 1735–1748. https://doi.org/10.1093/ia/iiae127.

Kawecki, D., Scheeder, P.R., Nowack, B., 2018. Probabilistic material flow analysis of seven commodity plastics in Europe. Environ. Sci. Technol. 52 (17), 9874–9888.

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the Circular Economy: evidence From the European Union (EU). Ecol. Econ. 150 (December 2017), 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour., Conserv. Recycl. 127 (April), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kirchherr, J., Yang, N.H.N., Schulze-Spüntrup, F., Heerink, M.J., Hartley, K., 2023. Conceptualizing the circular economy (revisited): an analysis of 221 definitions. Resour., Conserv. Recycl. 194 (April), 107001. https://doi.org/10.1016/j.resconrec.2023.107001.

Lase, I.S., Tonini, D., Caro, D., Albizzati, P.F., Cristóbal, J., Roosen, M., Kusenberg, M., Ragaert, K., Van Geem, K.M., Dewulf, J., De Meester, S., 2023. How much can chemical recycling contribute to plastic waste recycling in Europe? An assessment using material flow analysis modeling. In: Resour., Conserv. Recycl., 192. https://doi.org/10.1016/j.resconrec.2023.106916.

Lindberg, M.B., Markard, J., Andersen, A.D., 2019. Policies, actors and sustainability transition pathways: a study of the EU's energy policy mix. Res. Policy. 48 (10), 103668. https://doi.org/10.1016/j.respol.2018.09.003.

Maury, T., Tazi, N., Torres de Matos, C., Nessi, S., Antonopoulos, I., Pierri, E., Baldassarre, B., Garbarino, E., Gaudillat, P., Mathieux, F., 2023. Towards Recycled Plastic Content Targets in New Passenger Cars. Technical proposals and Analysis of Impacts in the Context of the Review of the ELV Directive, July. Publications Office of the European Union. https://doi.org/10.2838/834615.

Miles, M., Huberman, M., Saldaña, J., 2013. Qualitative Data Analysis: a Methods Sourcebook.

Milios, L., Holm Christensen, L., McKinnon, D., Christensen, C., Rasch, M.K., Hallstrøm Eriksen, M., 2018. Plastic recycling in the Nordics: a value chain market analysis. Waste Manag. 76, 180–189. https://doi.org/10.1016/j.wasman.2018.03.034.

Miller, L., Soulliere, K., Sawyer-Beaulieu, S., Tseng, S., Tam, E., 2014. Challenges and alternatives to plastics recycling in the automotive sector. Materials. (Basel) 7 (8), 5883–5902. https://doi.org/10.3390/ma7085883.

Nyffenegger, R., Baldassarre, B., Bocken, N., Grösser, S.. Circular business model experimentation in the solar industry. https://doi.org/10.13140/RG.2.2.13703.00165.

Nyffenegger, R., Baldassarre, B., Bocken, N., 2023. Circular business models and supporting policies for reusing of photovoltaic modules in the EU. In: Niinimäki, K., Cura, K. (Eds.), Product Lifetimes And the Environment 2023. Aalto University Publication Series, pp. 738–744. https://doi.org/10.13140/RG.2.2.24431.41124.

Odum, H.T., 1973. Energy, ecology, and economics. Ambio.

Paletta, A., Leal Filho, W., Balogun, A.L., Foschi, E., Bonoli, A., 2019. Barriers and challenges to plastics valorisation in the context of a circular economy: case studies from Italy. J. Clean. Prod. 241, 118149. https://doi.org/10.1016/j.jclepro.2019.118149.

Patton, M.Q., 2002. Qualitative interviewing. In: Qualitative Research and Evaluation Methods, 3.

Piila, N., Sarja, M., Onkila, T., Mäkelä, M., 2022. Organisational drivers and challenges in circular economy implementation: an issue life cycle approach. Org. Environ. 35 (4), 523–550. https://doi.org/10.1177/10860266221099658.

Pinto, J.T., Diemer, A., 2020. Supply chain integration strategies and circularity in the European steel industry. Resour., Conserv. Recycl. 153, 104517.

PlasticsEurope, 2020. Plastics – the Facts 2020. Plastics Europe.

PlasticsEurope, 2021. Plastics—the facts 2021 an analysis of European plastics production, demand and waste data. Plast. Europe 34. https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/.

Plastics Europe, 2022. The circular economic for plastics. An European overview. In: Plast. Europe, 81. https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-overview-2/.

Ranta, V., Aarikka-Stenroos, L., Ritala, P., Mäkinen, S.J., 2018. Exploring institutional drivers and barriers of the circular economy: a cross-regional comparison of China, the US, and Europe. Resour., Conserv. Recycl. 135 (December 2016), 70–82. https://doi.org/10.1016/j.resconrec.2017.08.017.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Foley, J.A., 2009. A safe operating space for humanity. Nature 461 (7263), 472–475. http://www.ncbi.nlm.nih.gov/pubmed/19779433.

Soo, V.K., Doolan, M., Compston, P., Duflou, J.R., Peeters, J., Umeda, Y., 2021. The influence of end-of-life regulation on vehicle material circularity: a comparison of Europe, Japan, Australia and the US. Resour., Conserv. Recycl. 168 (October 2020), 105294. https://doi.org/10.1016/j.resconrec.2020.105294.

Stahel, W.R., 1994. The Utilization-Focused Service Economy. Resource Efficiency and Product Life Extension. Green. Ind. Ecosyst. 178–190. https://books.google.com/books?hl=de&lr=&id=60XT8qeb1UoC&pgis=1.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science (1979) 347 (6223). https://doi.org/10.1126/science.1259855.

The Plastics Industry Trade Association, 2016. Automotive Recycling: devalued is now Revalued. Aseries on Economic-Demographic-Consumer & Technology Trends in Specific Plastics End Markets. https://www.plasticsindustry.org/sites/default/files/2016-03256-SPI-PMW-Auto-Recycle-web.pdf.

Trinomics, 2020. Evaluation of the Directive 2000/53/EC on End-of-Life Vehicles.

van Bruggen, A.R., Zonneveld, M., Zijp, M.C., Posthuma, L., 2022. Solution-focused sustainability assessments for the transition to the circular economy: the case of plastics in the automotive industry. J. Clean. Prod. 358 (April), 131606. https://doi.org/10.1016/j.jclepro.2022.131606.

Van Dam, K., Simeone, L., Keskin, D., Baldassarre, B., Niero, M., Morelli, N., 2020. Circular economy in industrial design research: a review. Sustainability.

Vermunt, D.A., Negro, S.O., Verweij, P.A., Kuppens, D.V., Hekkert, M.P., 2019. Exploring barriers to implementing different circular business models. J. Clean. Prod. 222, 891–902. https://doi.org/10.1016/j.jclepro.2019.03.052.

Vimal, K.E.K., Agarwal, V., Mathiyazhagan, K., 2022. Barriers in the adoption of buyback schemes for used plastic packaging material – a contextual relationship analysis. Resour., Conserv. Recycl. 178 (May 2021), 106084. https://doi.org/10.1016/j.resconrec.2021.106084.

Watkins, E., Romagnoli, V., Kirhensteine, I., Ruckley, F., Mitsios, A., Pantzar, M., Saveyn, H., Garbarino, E., 2020. Support to the circular plastics alliance in establishing a work plan to develop guidelines and standards on design-for- recycling of plastic products. European Commission JRC Report. https://doi.org/10.2760/936397.