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How much can chemical recycling contribute to plastic waste recycling in Europe? An assessment using material flow analysis modeling



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ABSTRACT

Plastic recycling rate in Europe is low, urging developments in recycling technology and strategies to increase circularity. Mechanical recycling (MR) has been the reference recycling technology for years, but in the near future chemical recycling (CR) options are expected to contribute to improve plastic circularity. This study uses a material flow analysis (MFA) at European level to provide quantitative estimates of the contribution of CR technologies to plastic recycling. Ten most used polymer types from five sectors are selected. A *status quo* 2018 scenario is modelled and compared to five potential future scenarios (in 2030) of plastic waste treatment, including one that only looks at improved waste collection, sorting, and MR technologies and four exploring developments of CR options. The so-called ‘missing plastics’, i.e., plastic waste generated but currently not accounted for in statistics, is considered in one of the future scenarios. The MFA results are compared by calculating four circularity indicators namely end-of-life recycling rate (EoL-RR), plastic-to-plastic rate, plastic-to-chemicals rate, and plastic-to-fuels rate. The results indicate that in the most optimistic scenario the EoL-RR in 2030 is 73–80% (sum of plastic-to-plastic and plastic-to-chemical rates, excluding plastic-to-fuel rate), in which 41–46% is plastic-to-plastic from MR, 15–38% is plastic-to-plastic from CR and 19–35% is plastic-to-chemicals. The highest achievable plastic-to-plastic rate is estimated to be 61% (46% from MR and 15% from CR). In all future scenarios, the plastic-to-fuel rate is estimated to be 3–6%. The MFA results are also used to estimate potential recycled content availability in 2030, which suggest that closed-loop recycling and processing the ‘missing plastics’ will be necessary to achieve the targets.

1. Introduction

Plastic is a bulk term for a wide range of polymers that is widely used in various applications due to their light weight, durability, affordability and broad application range (Lebreton and Andrady, 2019; Hsu et al., 2021). In 2019, global plastic use amounted to 460 million tonnes (Mt), of which more than 60% was used in the packaging, construction, and

automotive sectors. In the same year, 353 Mt of plastic waste were generated, of which only 6% was effectively recycled globally while the remaining mass was mostly incinerated or landfilled (OECD, 2022). Some studies also emphasize the leakage of macro- and micro-plastics into the environment (Ryberg et al., 2019; Peano et al., 2020; Boucher et al., 2020). Moreover, the demand for plastic, and the subsequent plastic waste generation, is expected to increase considerably in

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the coming years (Material Economics, 2022; Geyer et al., 2017; Balde et al., 2017). Thus, there is an urgent need to tackle plastic waste problems amongst others by increasing the circularity of the plastic value chain.

According to Plastics Europe (2020), Europe generated 29.1 Mt of plastic waste in 2019. Of the generated plastic waste in 2019, it is estimated that 19.6 Mt (i.e., 67%) was landfilled or incinerated and only 9.4 Mt (i.e., 33%) was sent to recycling facilities (Plastics Europe, 2020). Further, it is estimated that out of the plastic waste sent to recycling in 2019, only 4 Mt were effectively recycled, hence resulting in recycling rates of approx. 15–33%, depending on the calculation methods (Plastics Europe, 2020; Agora Industry, 2022). The 33% plastic recycling rate is calculated based on the quantity of plastic waste entering recycling facilities over the reported plastic waste generation (Plastics Europe, 2020). The 15% plastic recycling rate is calculated based on the quantity of recycled plastic production (after regranulation) over the total estimated plastic waste generated (i.e., reported plastic waste quantity plus the ‘missing plastic’) (Agora Industry, 2022). According to Material Economics (2022), the reported amount of plastic waste in Europe (i.e., 29.1 Mt) is deemed to be underestimated as substantial amounts are seemingly not accounted for (so-called ‘missing plastic’) in the statistical databases, e.g., municipal waste statistics. Studies from Agora Industry (2022) and SYSTEMIQ (2022) estimate that 7–15 Mt of plastic waste are ‘missing’ because of either underestimation of plastic in mixed (municipal) waste, underestimation of lifetime of plastic applications, or unidentified/undocumented flows (e.g., unauthorised waste treatment or exports of waste).

Reinforcing the efforts to improve the plastic circularity in Europe, the European Commission (EC) has enacted several regulations, along with (voluntarily) pledges made by stakeholders in the plastic value chain (e.g., by cars and electronic products manufacturers). For example, 55% of plastic packaging waste should be recycled by 2030 as stated in the Packaging and Packaging Waste Directive (PPWD) (European Commission, 2018a). Cars and electronic manufacturers also pledge to use 25–30% of recycled plastic in their new products by 2030 (Maury et al., 2022; Sandoval, 2018; Volvo, 2018). The Landfill Directive also limits municipal waste to be landfilled in 2035 by 10% (European Commission, 2018b). The complete list of relevant laws and pledges is available in Table S1. The regulations and pledges also aim to enhance the uptake of recycled plastic in new products (i.e., recycled content), which would increase the demand and potentially the price of recycled plastics (Maury et al., 2022; European Commission, 2022a). However several studies indicate that either the targets are not yet accomplished or significant improvements are still needed to achieve the targets. Lase et al. (2021) suggest that the recycled content targets in the electronic sector will be difficult to achieve in Belgium and the Netherlands due to inefficiencies in collection, sorting and recycling chains. Studies from Maury et al. (2022), Cardamone et al. (2022), and Williams et al. (2020) suggest that plastic from end-of-life vehicles (ELVs) are treated with less attention to polymer recovery and the ‘reuse and recycling’ target from ELV (i.e., 85%) stated in the End-of-Life Vehicles Directive (ELVD) is mainly achieved by recycling aluminum and metals from ELVs, leaving a substantial amount of plastic to be landfilled or incinerated. Similarly, a significant amount of plastics packaging waste is not separately collected, correctly sorted or recycled, while substantial improvements are needed to meet the 55% recycling target by 2030 stated in the PPWD (Picuno et al., 2021; Antonopoulos et al., 2021; Lopez-Aguilar et al., 2022; Van Eygen et al., 2018). It is thus clear that the circular economy for plastic needs an urgent boost.

The ways to improve plastic circularity and recycling rates in Europe are two-fold: implementation of plastic *production and use-oriented* solutions, and *end-of-life (EoL) treatment-oriented* solutions. *Production and use-oriented* solutions typically focus on improving products’ design for easier EoL treatment (i.e., design-for-recycling principles), reducing material complexity (e.g., by changing from multi- to mono-material), reducing plastic use in a product (e.g., reduce packaging weight or

unused space for packaging), and fostering new delivery business models (e.g., through promoting reuse) (OECD, 2022; SYSTEMIQ, 2022; Feber et al., 2020). On the other hand, the *EoL treatment-oriented* solutions focus on improving the existing waste management infrastructure and practices such as promoting separate collection, sorting per polymer group, and advancing recycling technologies (Ellen MacArthur Foundation, 2016; PRI, 2019).

Related to EoL solutions, today, mechanical recycling (MR) is still the most commercially used technique to recycle plastic (over 9.0 Mt processing capacity), while chemical recycling (CR) and solvent-based recycling (SBR) is treating only less than 0.2 Mt of plastic waste in Europe (Plastics Europe, 2019a). However, MR faces several challenges in treating plastic waste, such as thermal-mechanical degradation, the presence of legacy additives and chemicals, and inadequate technical properties of the final regranulates to meet the market demands (Ragaert et al., 2017; Simon and Martin, 2019; Eriksen et al., 2020). Also, potential degradation might occur by multiple rounds of recycling (Demori et al., 2015; Pérez et al., 2010; Schyns and Shaver, 2021; Arena and Ardolino, 2022). Several improvements can be implemented to tackle these MR challenges such as the implementation of advanced (pre-)treatment processes (e.g., deinking and deodorization), advanced washing (e.g., hot washing with detergents) and improved extrusion (e.g., double melt filtration) (Lase et al., 2022; Kol et al., 2021; Roosen et al., 2021; Demets et al., 2020). Nevertheless, even after elaborated sorting process, some plastic waste streams remain unsuitable for MR due to the heterogeneous composition (e.g., mixed of rubbers, thermosets, and thermoplastics), substantial level of hazardous substances (e.g., legacy chemicals from flame retardants), or multi-material structures (e.g., fiber-reinforced composites or metalized packaging) (Cardamone et al., 2022; Arena and Ardolino, 2022).

On the other hand, several studies predict that CR technologies (i.e., pyrolysis, gasification, depolymerization) and SBR technologies (i.e., dissolution-precipitation, deinking, delamination) will play a big role in the future plastic waste treatment in Europe (Simon and Martin, 2019; Hann and Connock, 2020; Crippa et al., 2019; Manžuch et al., 2021). These technologies are claimed to have a higher tolerance in dealing with contaminated and complex waste streams, i.e., waste streams that are not recycled yet due to the limitation of current state-of-the-art MR (SYSTEMIQ, 2022; Cardamone et al., 2022; Arena and Ardolino, 2022; Vollmer et al., 2020; Solis and Silveira, 2020). Several plans to build CR plants have been announced such as gasification plant in Spain (treating non-recyclable mixed solid waste with 400,000 tonne/year capacity), pyrolysis plant in Spain and Belgium (treating mixed polyolefin and polystyrene with up to 65,000 tonne/year capacity), and chemical depolymerization plant in the United Kingdom, France, Belgium, and Spain (treating polyurethane; 2000 tonne/year capacity and polystyrene; 15,000 tonne/year capacity) (Indaver, 2022; INEOS Styrolution, 2021; AIMPLAS, 2022). In this sense, CR and SBR technologies are perceived as complementary to treat plastic waste streams that otherwise would have been landfilled or incinerated (Arena and Ardolino, 2022; Manžuch et al., 2021). From a life cycle perspective, diverting plastic waste streams from landfill, incineration, and export outside Europe (e.g., to African and Asian countries; Huisman et al., 2012; Jacobs et al., 2018) leads to environmental benefits by simultaneously avoiding such sub-optimal management practices and producing new secondary materials to replace production of virgin ones. Several studies indeed indicate better environmental performance of CR plastic waste compared to landfill and incineration (Arena and Ardolino, 2022; Vollmer et al., 2020; Demetrious and Crossin, 2019; Civancik-Uslu et al., 2021; Schwarz et al., 2021; Eschenbacher et al., 2022). However, while some studies have preliminarily investigated the environmental benefits (Arena and Ardolino, 2022; Vollmer et al., 2020; Civancik-Uslu et al., 2021; Jeswani et al., 2021) and technical feasibility (Kusenberget al., 2022a, 2022b; Larrain et al., 2020; Genuino et al., 2022) of some CR and SBR technologies, research on the performance and on the role and deployment of these technologies at industrial scale

in the future Europe plastic waste management system is still scarce. Moreover, CR options such as pyrolysis and gasification produce not only monomers but also other base chemical products (i.e., benzene, toluene, xylene, wax, etc.) and fuels (i.e., hydrocarbons as synthesis gas or oil) (Kusenberget al., 2022c, 2022d). Nevertheless, such variety of outputs, while certainly contributing to plastic circularity, poses legal challenges as fuel- and energy-like outputs are not considered under ‘recycling’ in the Waste Framework Directive (WFD) (European Commission 2018a, 2008).

In the context of the urgent need to increase the circularity of plastics, and to achieve (voluntary) targets or pledges, CR and SBR could play a pivotal role. However there is little quantitative evidence (and data available) on how big this contribution might be. Hence, study investigates the current and future flows of ten most used plastic waste throughout the plastic waste management systems (of five different sectors) in Europe. A material flow analysis (MFA) model based on mass balance principles is developed and used. Six scenarios are developed and discussed: i) *status quo* scenario in 2018 (S0, as benchmark) and ii) five potential future scenarios in 2030 (S1 – S5), including improving only collection, sorting, and MR as well as a combination of improved MR, CR, and SBR of plastic waste. One of the future scenarios also investigates the contribution of processing the so-called ‘missing plastics’ according to *Material Economics* (2022); *Agora Industry* (2022) and *SYSTEMIQ* (2022). The selection of suitable CR and SBR options in this study is determined by considering the capability of the CR and SBR options to treat plastic waste streams, including the type and composition of the streams as recently reported by the stakeholders to the EC.

For each scenario, a set of circularity indicators of plastic waste treatment are calculated based on MFA, namely: *EoL recycling rates* (EOL-RR), *plastic-to-plastic* (P2P), *plastic-to-chemicals* (P2C) and *plastic-to-fuels* (P2F) rates in order to assess the potential improvements when CR and SBR options are implemented at large scale. This study thus includes the amounts of materials produced such as polymers (i.e., recycled plastics from MR, CR, and SBR), base chemicals (e.g., wax, benzene, toluene, xylene from CR), and fuels (e.g., synthesis gas from CR). Lastly, the potential of recycled content availability in 2030 from different scenarios is quantified and discussed, which is based on the share of recycled plastic production (per sector) over plastic demand (per sector) in 2030.

2. Materials and methods

2.1. General modeling approach

This study focuses on the ten most used polymers in the European Union (EU) 27+3 (Norway, Switzerland, and the United Kingdom) (Plastics Europe, 2019) with high data availability in all life cycle stages from production to the EoL treatment (Eriksen et al., 2020; Kawecki et al., 2018) and considered as priority products within the plastic industry (Watkins et al., 2020). The ten polymers considered in scope within this study are Linear Low Density Polyethylene (LLDPE), High Density Polyethylene (HDPE), Polypropylene (PP), Poly(ethylene Terephthalate) (PET), Polystyrene (PS), Expanded Polystyrene (EPS), Poly(vinyl Chloride) (PVC), Acrylonitrile Butadiene Styrene (ABS), Polyurethane (PUR), and Polyamide (PA). These polymers are applied in different sectors with their specific use and EoL fate. The five sectors included in this study are: packaging, building and construction, automotive, electronic, and agriculture sector. Overall the selected polymers and sectors in this study cover 60% of the total reported plastic waste in 2018 in EU 27+3 (Plastics Europe, 2019a, 2019b). The other 40% of polymers that are not considered in this study (which is subjected for future research) include waste from household goods, textiles, and others (e.g., medical) (estimated to be 15–25%, based on *Plastics Europe*, 2019a) and some polymer types (e.g., Polycarbonate or Poly(methyl methacrylate), etc.) in packaging, electronic and automotive sectors (up to 35% of ‘other polymers’, based on *Plastics Europe*, 2019a

and 2019b).

The MFA of the selected polymers is modelled by following four steps, following the methodology from previous studies (Antonopoulos et al., 2021; Eriksen et al., 2020; Kawecki et al., 2018). Firstly, the required inputs data for MFA model are gathered: (i) a process diagram of the current (and future) plastic waste management systems in EU 27+3, (ii) the respective transfer coefficients (TCs, in%) of each process, and (iii) the quantities of the selected polymers (in kilo tonnes, kt). The TCs describe the partitioning of mass input(s) to output(s) for each process in the system. The MFA model quantifies the mass balance (in kt) throughout the defined system that is obtained by multiplying the mass input quantity with the TCs of each process in the system. Secondly, *status quo* scenario and five potential future scenarios are developed, representing the flow of the selected polymers in 2018 and potential flows in 2030, respectively. In order to model the mass flows in 2030, projections of waste quantities, improvements of the TCs, and recycling pathways (MR, CR, and/or SBR options) are implemented. Thirdly, the MFA results from the six different scenarios are assessed and compared by calculating four selected circularity indicators. Lastly, for each output (material flows and circularity indicators), the parametrical input uncertainties are propagated into output uncertainties. The uncertainty propagation with Monte Carlo simulation is performed and the standard deviation of the mass flow is calculated. The standard deviation is calculated assuming a Triangular Distribution (TD) of the dataset and the values are selected based on the relevant literature of plastic waste management in EU 27+3.

2.2. Defining the scope of recycling technologies

After plastic waste is collected and sorted, MR, CR and SBR routes can be chosen. MR refers to mechanical reprocessing by means of shredding, washing, drying, and extrusion of polymers without breaking down the polymer chains. CR refers to a reprocessing technologies that break down the polymer chains and converts them into high added-value materials, such as oligomers, monomers, base chemicals, and hydrocarbons (solid, liquid, or gas) (Arena and Ardolino, 2022; Hann and Connock, 2020; Crippa et al., 2019; Manžuch et al., 2021). However, CR is an umbrella term that has been used to cover a broader set of technologies (Hann and Connock, 2020; Manžuch et al., 2021), such as thermal depolymerization (i.e., pyrolysis coupled with steam cracking or gasification coupled with Fischer-Tropsch Synthesis) and chemical depolymerization (i.e., glycolysis, methanolysis, etc.). SBR (also known as ‘physical’ or ‘material’ recycling) refers to material reprocessing by means of dissolving the polymer (or additives and pigments), in which the impurities is removed while the polymer is recovered through filtration or extraction phase (Crippa et al., 2019). A more detailed explanation of each technology at process level can be found in the Supporting Information (SI)–Section 2.

2.3. Material flow analysis model development

2.3.1. Description of system boundaries and scenarios

This study focuses on Europe as EU27+3 as most of the datasets used in this study cover this region (Eriksen et al., 2020; *Plastics Europe*, 2019b; Kawecki et al., 2018; Watkins et al., 2020; Hestin et al., 2017). The diagram of the system boundaries can be found in Fig. 1. The boundary comprises collection, sorting, and recycling, including the future potential plastic recycling using CR technologies in 2030. Fig. 1 illustrates the waste management systems for plastic waste in the EU27+3 per sector. Detailed information on the waste management systems per sector can be found in the SI–Section 3. There are three potential destinations of the plastic waste treatment: i) secondary materials to be used in the economy again, ii) waste streams that are sent for residual treatment (i.e., incineration or landfilling), and iii) waste export and/or informal waste treatments (Fig. 1). As for the waste that is informally treated, the whereabouts of these flows are difficult to track.

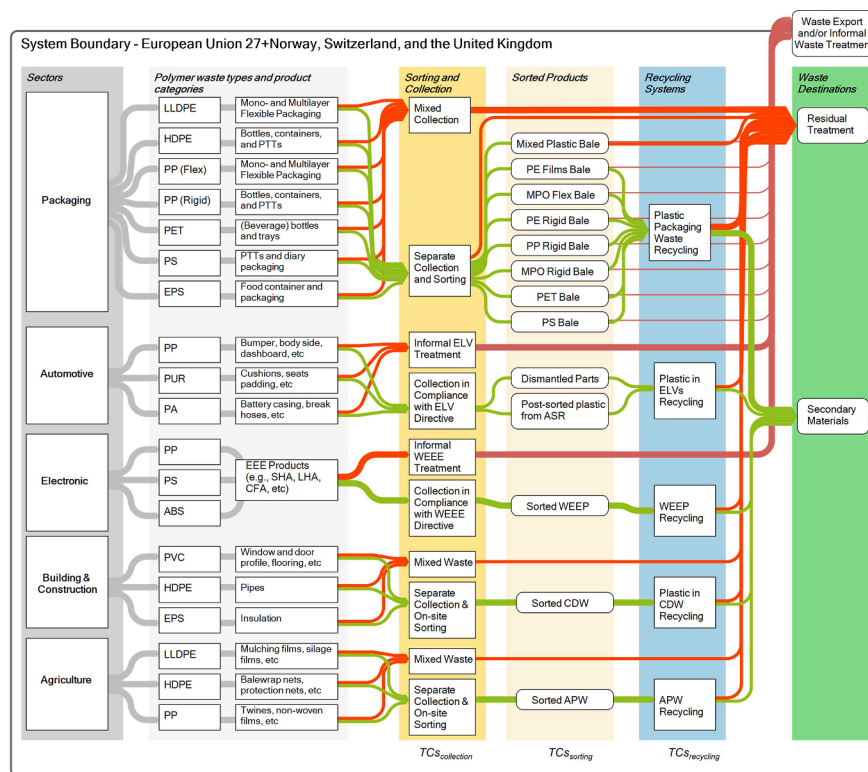


Fig. 1. Conceptual diagram of the end-of-life treatment of the selected plastic waste from different sectors considered in this study. The thickness of the arrows does not represent mass/quantity. Abbreviations: ABS (Acrylonitrile Butadiene Styrene), APW (agriculture plastic waste), ASR (automotive shredder residue), CDW (construction and demolition waste), CFA (cooling and freezing appliance), EEE (electronic and electrical equipment), ELV (end-of-life vehicle), EPS (Expanded Polystyrene), HDPE (High Density Polyethylene), LLDPE (Linear Low Density Polyethylene), LHA (large household appliance), PA (Polyamide), PET (Polyethylene Terephthalate), PP (Polypropylene), PS (Polystyrene), PTTs (Pots, trays, and tubes), PUR (Polyurethane), PVC (Polyvinyl Chloride), SHA (small household appliance), TCs (transfer coefficients), WEEE (waste electronic and electrical equipment), WEEP (waste electronic and electrical plastic).

However, several studies suggest potential destination of these flows such as unreported recycling within EU 27+3, illegal export outside EU 27+3 (can be partially recycled), or leakage to the environment (Ryberg et al., 2019; Peano et al., 2020; Boucher et al., 2020; Lase et al., 2021). Note that in this study the legal waste export from EU 27+3 to other countries is merged together with ‘informal waste treatments’ due to limited data available to estimate exact fate of these flows, which has been pointed out by previous studies (Material Economics, 2022; Agora Industry, 2022; SYSTEMIQ, 2022; Lase et al., 2021). Plastic packaging waste export (including non-household waste) usually occurs after a certain degree of separate collection (and sometimes partial sorting), i. e., 25% of the sorted bales are sent to countries outside EU27+3, as suggested by Antonopoulos et al. (2021). The plastic waste treatment of the exported waste at their final destinations (e.g., to Southeast Asia or African countries) is poorly reported, however it is a combination of recycling parts of it, with illegal dumping, unsanitary landfill, or open burning of residues (Tran, 2018; Wang, 2014; Liang et al., 2021; Petrlik et al., 2019; Chen et al., 2021; Lasaridi et al., 2018; Lase et al., 2021).

In this study, six scenarios are modelled (Table 1): one scenario as benchmark (i.e. the *status quo* in 2018) (S0), and five potential future scenarios in 2030 (S1–S5). The future scenarios take into account the feedstock type, composition, technology readiness level, and few improvements within the waste management systems (e.g., PP flex packaging waste could be separated from the mixed films streams; Lase et al., 2022). Table 1 also summarizes the supporting argumentations and assumptions of the five potential future scenarios in 2030, including information on the feedstock to CR and SBR options and their output(s). Moreover, it is assumed that the rate of waste export in 2030 will be significantly lower compared to the *status quo* scenario in 2018 because of two reasons. First, the implementation of CR and SBR is expected to allow more heterogeneous waste streams to be reprocessed inside EU27+3 and second, stricter regulations of transboundary waste shipment (e.g., as mandated by UNEP Basel Convention; Lasaridi et al., 2018). It is important to note that indeed other scenarios might enroll in future work too, based on new developments and insights.

S1 illustrates the improvements of current state-of-the-art plastic

waste management systems, following the trends of increased collection rates and improved sorting and MR technologies (Maury et al., 2022; Lase et al., 2021; Antonopoulos et al., 2021). S1 assumes that only MR will be deployed to treat plastic waste. S2 serves as ‘explorative’ projections, in which CR and SBR are assumed to outcompete MR (technologically and quantity wise) to deal with plastic waste. In S2, all sorted plastic waste, including the rejects from sorting and MR (i.e., 90–100% of mass, SYSTEMIQ, 2022) and mixed waste streams (i.e., 50–80% of mass, SYSTEMIQ, 2022) are assumed to be processed via CR. S3 investigates the CR and SBR options as an alternative technology to MR option. In S3, it is assumed that CR and SBR options would take a small share of plastic waste stream that is already mechanically recycled (i.e., 1–20% mass), including rejects (i.e., 90–100% mass, SYSTEMIQ, 2022) and mixed waste streams (i.e., 50–80% mass, SYSTEMIQ, 2022). S3 assumes that MR still outcompetes CR and SBR (technologically and quantity wise) in processing sorted plastic waste. Also, it is assumed in S3 that CR and SBR will only process low quantities of sorted plastic in 2030 because they encounter several operational (and technical) issues to scale up the technologies at industrial scale (Jehano et al., 2022; Coates and Getzler, 2020; Tukker et al., 1999). Manžuch et al. (2021) and Kusenberget al. (2022e) also indicates that significant improvements are needed to upgrade pyrolysis oil as well as feedstock quantity (and quality) for industrial steam crackers. Improvements are also still needed to scale up and optimize SBR technique (Jehano et al., 2022; Coates and Getzler, 2020; Tukker et al., 1999). Hence, S3 can also be perceived as ‘sub-optimal’ CR and SBR implementation, while MR is still chosen to be the main recycling technology. Furthermore, S4 investigates CR as complementary technology to MR for waste streams that otherwise would be landfilled or incinerated. In S4, CR is assumed to process mixed polyolefin (PO) packaging (rigid and flexible) bales, mixed plastic packaging bales, 50–80% rejects, and 90–100% mixed waste streams. Notice that in the development of this scenario we strive to learn from, and to the extent possible align with, precedent studies that investigated the potential role of CR and SBR in the future in EU 27+3 (in S4, notably SYSTEMIQ, 2022; Arena and Ardolino, 2022; Hann and Connock, 2020; Manžuch et al., 2021). Finally, S5 is identical

Table 1

Overview of the developed scenarios for the MFA of plastic waste in European Union 27+Norway, Switzerland, and the United Kingdom. ABS (Acrylonitrile Butadiene Styrene), APW (agriculture plastic waste), CDW (construction and demolition waste), CR (Chemical recycling), ELV (end-of-life vehicle), MR (Mechanical recycling), PE (Polyethylene), PA (Polyamide), PET (Polyethylene Terephthalate), PP (Polypropylene), PS (Polystyrene), PUR (Polyurethane), PVC (Polyvinyl Chloride), SBR (solvent-based recycling), TCs (transfer coefficients), TD (Triangular distribution), WEEP (waste electronic and electrical plastic).

Scenarios	Supporting argumentation	Description	Input(s) for CR and SBR	Output(s) from CR and SBR
S0: Status quo in 2018 S1: Plastic waste treatment via MR in 2030	Benchmark (reference) scenario Improvement in waste collection rate, sorting, and MR in 2030 towards breakthrough of (currently) known best practices in 2022 based on previous studies (Maury et al., 2022; Lase et al., 2021; Antonopoulos et al., 2021).	Flows of plastic waste in 2018 Improved TCs of waste collection rate, sorting, and MR yield in 2030 towards. The rejects (from sorting and MR) and mixed waste streams are sent to residual treatment	Not applicable Not applicable	Not applicable Not applicable
S2: Plastic waste treatment via CR and SBR in 2030	‘Explorative’ projections of plastic waste management in which CR and SBR options technologically outcompetes MR option	All sorted plastic are sent to CR or SBR, including 50–80% rejects from sorting and MR (assuming TD) and 90–100% mixed waste streams (assuming TD) in 2030	Dissolution-precipitation: <ul style="list-style-type: none"> Sorted PVC and PS from CDW Chemical depolymerization: <ul style="list-style-type: none"> Sorted PET bales (packaging sector) Manually dismantled and post-sorted PA and PUR from ELVs Pyrolysis with Steam Cracking: <ul style="list-style-type: none"> Sorted PE film, PP film, PE rigid, PP rigid, mixed PO (film and rigid), and mixed plastic film bales (packaging sector) Manually dismantled and sorted PP from ELVs Sorted PP, PS and ABS from WEEP Sorted PE and PP from CDW and APW Gasification with Fischer-Tropsch Synthesis: <ul style="list-style-type: none"> Rejects from sorting and MR Mixed waste streams 	Chemical depolymerization and dissolution-precipitation: <ul style="list-style-type: none"> Polymer (and flakes for dissolution-precipitation) Pyrolysis with Steam Cracking: <ul style="list-style-type: none"> Polymer Base chemicals (e.g., wax, benzene, toluene, xylene, etc.) Fuels (i.e., synthesis gas) Gasification with Fischer-Tropsch Synthesis: <ul style="list-style-type: none"> Polymer Base chemicals (e.g., tar, benzene, toluene, xylene, etc.) Fuels (i.e., synthesis oil)
S3: Plastic waste treatment via MR and CR in 2030, in which MR option still technologically outcompetes CR and SBR options	‘Sub-optimal’ CR and SBR implementation, while MR is still chosen as the main recycling option. Sub-optimal implementation is caused by operational (and technical) issues to scale up CR and SBR technologies to industrial scale (Jehano et al., 2022; Coates and Getzler, 2020; Tukker et al., 1999) and the need to optimize CR and SBR technologies (Manzuch et al., 2021; Kusenberger et al., 2022e).	Improved TCs of collection, sorting, and MR yield in 2030, while CR or SBR treats 1–20% mass (assuming TD) of sorted plastic waste from different sectors that is already sent to MR (in S1). Plastic waste in reject (50–80%, assuming TD) and mixed waste streams (90–100%, assuming TD) are also sent to CR in 2030	Dissolution-precipitation: <ul style="list-style-type: none"> Sorted PVC and PS from CDW Chemical depolymerization: <ul style="list-style-type: none"> Sorted PET bales (packaging sector) Manually dismantled and sorted PA and PUR from ELVs Pyrolysis with Steam Cracking: <ul style="list-style-type: none"> Sorted PE film, PP film, PE rigid, PP rigid, mixed PO (film and rigid), and mixed plastic film bales (packaging sector) Manually dismantled and sorted PP from ELVs Sorted PP, PS and ABS from WEEP Sorted PE and PP from CDW and APW Gasification with Fischer-Tropsch synthesis: <ul style="list-style-type: none"> Rejects from sorting and MR Mixed waste streams 	Chemical depolymerization and dissolution-precipitation: <ul style="list-style-type: none"> Polymer (and flakes for dissolution-precipitation) Pyrolysis with Steam Cracking: <ul style="list-style-type: none"> Polymer Base chemicals (e.g., wax, benzene, toluene, xylene, etc.) Fuels (i.e., synthesis gas) Gasification with Fischer-Tropsch Synthesis: <ul style="list-style-type: none"> Polymer Base chemicals (e.g., tar, benzene, toluene, xylene, etc.) Fuels (i.e., synthesis oil)
S4: Plastic waste treatment via MR and CR in 2030, in which CR options serve as complementary technology to treat waste streams that otherwise would be landfilled or incinerated	CR as complementary technology to MR for waste streams that otherwise would be landfilled or incinerated such as mixed PO packaging (rigid and flexible) bales, mixed plastic packaging bales, rejects, and mixed waste streams. (SYSTEMIQ, 2022; Arena and Ardolino, 2022; Hann and Connock, 2020; Manzuch et al., 2021).	Improved TCs of collection, sorting, and MR yield in 2030, while CR treats mixed PO bales, mixed plastic bales, mixed waste (90–100%, assuming TD) and the reject streams from sorting and MR (50–80%, assuming TD) in 2030	Relevant to S4 and S5 : Chemical depolymerization: <ul style="list-style-type: none"> Sorted PA from ELVs Pyrolysis: <ul style="list-style-type: none"> Mixed Plastic bales and Mixed Polyolefin (MPO) bales Gasification: <ul style="list-style-type: none"> Rejects from sorting and MR 	Relevant to S4 and S5 : Chemical depolymerization: <ul style="list-style-type: none"> Polymer Pyrolysis with Steam Cracking: <ul style="list-style-type: none"> Polymer Base chemicals (e.g., wax, benzene, toluene, xylene, etc.)

(continued on next page)

Table 1 (continued)

Scenarios	Supporting argumentation	Description	Input(s) for CR and SBR	Output(s) from CR and SBR
			<ul style="list-style-type: none"> o Mixed waste streams 	<ul style="list-style-type: none"> o Fuels (i.e., synthesis gas) Gasification with Fischer-Tropsch Synthesis: o Polymer o Base chemicals (e.g., tar, benzene, toluene, xylene, etc.) o Fuels (i.e., synthesis oil)
S5: Plastic waste treatment via MR and CR in 2030, in which CR options serve as complementary technology to treat waste streams that otherwise landfill or incinerated, including the 'missing plastic' in 2030		Identical to S4, with extra mass from accounting the 'missing plastic' (Plastics Europe, 2020; Plastics Europe, 2019b)		

to S4 but accounts for the extra plastic mass (in kt) derived from the 'missing plastic', and explores the impact of processing 'missing plastic' on the overall performance of plastic waste treatment in EU 27+3. When the quantities of 'missing plastic' are normalized to the total plastic demand in Europe in 2019 and 2020 (Plastics Europe, 2020, 2019b), they account for 15–30% of the total plastic demand. A more detailed description of the explorative future scenarios and improvements per sector is reported in the SI–Section 3.

2.3.2. Transfer coefficients

For the purpose of calculating the uncertainty of the outputs, the TCs are assumed to have a Triangular Distribution (TD) to cover the diversity of the information from several studies. The full list of TCs for the listed scenarios in 2018 and 2030, together with the corresponding TD, can be found in Table S2–S6. Essentially, the study of Watkins et al. (2020) is used as the primary data points to model the flows of plastic in 2018. Additionally, a few studies are selected to be the key literature studies to compare or complement the TCs presented and used by Watkins et al. (2020). Table S2–S6 provides information on the key literature that provide the TCs for the MFA modeling in the year 2018. Moreover, the approach to estimate TCs for the MFA model in 2030 as well as the TCs for CR and SBR are elaborated in the next sections.

2.3.2.1. Improved transfer coefficients in 2030 for collection, sorting, and mechanical recycling. To model the flows of plastic in 2030, it is assumed that the collection rate, sorting, and MR yield will improve. For collection, improvements of the collection rates are extrapolated (and projected in 2030) using linear regression based on the past reported collection rate from several sources (Hestin et al., 2017; Global E-Waste Statistics Partnership, 2022; Eurostat, 2021; 2022a, 2022b). From the linear regression calculations, the annual growth of the collection rates from 2018 to 2030 are obtained. For the packaging sector, the projection is based on Hestin et al. (2017) in 2012–2014. The annual growth of collection rate is estimated to be 4.0%. For the automotive sector, the collection rate is calculated as the share (or ratio) of the reported ELV recycling over ELV waste generated from Eurostat (2021) in 2010 – 2019. The annual growth of ELV collection rate is estimated to be 1.4%. Similarly, the collection rate of waste electronic and electrical equipment (WEEE) is calculated as the share (or ratio) of the reported WEEE generation (Global E-Waste Statistics Partnership, 2022) over the collected WEEE (Eurostat 2022b) in 2015 – 2019, with the annual growth of collection rate equal to 1.4%. For the building & construction and agriculture sector, it is assumed that the improvements of the collection rates are similar to the annual growth of the respective waste generation, i.e., annual growth of 0.8% for construction and demolition waste (CDW) and 1.0% for agriculture plastic waste (APW) (more in the

next section).

The improvement of sorting and MR yields in 2030 are projected by assuming that the best practices of plastic waste sorting and recycling will be reached by 2035 (Antonopoulos et al., 2021). The assumption illustrates the optimization and widespread implementation of best available technologies in sorting and recycling different polymers across different sectors by 2035. The whole dataset in Table S2–S6 is used to calculate the uncertainty of the flows in 2030. Through this approach, the annual growth of sorting and recycling yields are calculated for different polymers across different sectors. More detailed information on the projections of collection rate, sorting, and recycling yields can be found in Figure S10–S22.

2.3.2.2. Transfer coefficients of chemical and solvent-based recycling. Pyrolysis, coupled with Distillation, Hydrotreatment, and Steam Cracker. The first steps of the (after the plastic waste is separately collected and sorted) are shredding, cold washing (to remove contaminants like organic and inorganic residue; Lase et al., 2022) and extrusion (using extrusive dehalogenation technique to remove substances like PVC and flame retardants; Kusenberg et al., 2022e). Afterwards, the plastic wastes are fed into the cracking and condensation reactor to produce pyrolysis oil that is distilled into naphtha and wax. The naphtha is fed into the steam crackers (with pyrolysis oil upgrading such as hydro-treatment) to produce monomers, which are used as a feedstock to recreate polymers again, and base chemicals. The TCs of the shredding, washing, and extrusion of MPO and Mixed Plastic bales are adopted from Lase et al. (2022) and Civanvik-Uslu et al. (2021). The TCs from the cracking and condensation until (re)polymerization are obtained from literature (Civanvik-Uslu, 2021; Kusenberg et al., 2022a; Kusenberg et al., 2022b; Larrain et al., 2020; Jeswani et al., 2021; Genuino et al., 2022; Ghalomi et al., 2021; Zayoud et al., 2022; Kusenberg et al., 2022e).

Gasification, coupled with Fischer-Tropsch Synthesis: the processing of mixed waste and reject streams (from sorting and MR) via gasification starts with shredding the plastic waste into flakes followed by feeding them into gasification reactors to create mainly syngas with a small fraction of tar and char. The syngas is processed through Fischer-Tropsch Synthesis (FTS) to create monomers (incl. other base chemicals) that are used as feedstock for repolymerization processing. The TCs for converting plastic waste into syngas are obtained from literature (Mastellone, 2019; Lopez et al., 2018; Brems et al., 2015; Mastellone and Zaccariello, 2013; Arena, 2012). Lastly, the TCs for FTS and (re)polymerization are estimated from Zhao et al. (2021), Lee et al. (2008), and Jeswani et al. (2021).

Chemical depolymerization (i.e., glycolysis, methanolysis, aminolysis, etc.) is mainly implemented on sorted PET, PA, and PUR. The process

starts with shredding and washing followed by depolymerization. The TCs for shredding and washing are estimated from Larrain et al. (2020) and Lase et al. (2022), while the TCs for depolymerization are obtained from Kol et al. (2021), Vollmer et al. (2020), Schwarz et al. (2021), Shen et al. (2010), and Nikje et al. (2011).

Solvent-based recycling (e.g., dissolution-precipitation) is employed to dissolve the polymer waste using a solvent, followed by the removal of additives through filtration or phase extraction to recover the dissolved polymer and the solvent (Crippa et al., 2019). The TCs for solvent-based purification are estimated from literature (Schwarz et al., 2021; Naviroj et al., 2019). More detailed information on the TCs for CR and SBR considered and used in this study can be found in Table S7–S11.

2.3.3. Waste categories and quantities

2.3.3.1. Waste quantity in 2018. Table SI12 shows the waste categories and quantities (in kilo tonne, kt) used in this study, including some examples of the relevant products of the respective category. The estimation of waste quantities in 2018 is mainly based on Watkins et al. (2020). Within the packaging group, the share of mono- and multi-layer flexible packaging is estimated to be 80% and 20%, respectively (Lase et al., 2022). The share of bottles and pots, trays and tubes (PTTs) for PP rigid, HDPE, and PET is estimated from Hestin et al. (2017). The quantities of EPS foam are estimated from Hestin et al. (2017), i.e., 33% of the total PS in the packaging sector. In the automotive sector, the quantities of PA is estimated to be 12% of the total polymer used (Maury et al., 2022; European Commission, 2020). Lastly, the quantities of PP and ABS used in the electronic sector are estimated from Lase et al., (2021) and European Commission (2020).

2.3.3.2. Estimation of waste quantity in 2030 based on historical data extrapolation. The quantities of the selected polymers in 2030 are extrapolated using linear regression based on the historical waste generation found in statistical databases (Eurostat, 2021, 2022a, 2022b, 2022c), e.g., from 2010 to 2018 in packaging sector based on data availability for EU27+3 found in Eurostat (2022a), more in Figure S23–S27. Later, the information on the annual growth per sector is extracted and applied to estimate the quantities of waste in 2030 (see Table SI12). For the packaging, automotive, and electronic sector, the projections are based on the historical packaging waste, ELV, and WEEE generation based on Eurostat (2021, 2022a, 2022b). Regarding the projections of waste quantities for building & construction and agriculture sectors, historical waste quantity data by NACE activity (NACE F: Construction and NACE A: Agriculture, forestry, and fishing, respectively) are extracted from Eurostat (2022c). Overall the annual growth rates for packaging, ELV, WEEE, CDW, and APW are 1.4–1.8%, 1.3–1.6%, 1.1–1.2%, 0.8–0.9%, and 1.0–1.1%, respectively. Detailed results of the projections and annual growth can be found in Supplementary Materials, section 8.

2.4. Circularity indicators

The summary of the four circularity indicators can be found in Table 2 (Eqs. 1–8). In Fig. 2, a conceptual diagram of life cycle of plastic is presented to show the calculation point of each indicator. The *end-of-life recycling rate* (EoL-RR) (measured in%) is calculated as the ratio between the total mass (in kt) of polymer and base chemicals ($\mu_{\text{polymer}} + \mu_{\text{base chemicals}}$) that is produced from the plastic waste treatments over the waste generated ($\mu_{\text{waste generation}}$) (in kt) (UNEP, 2011; Perio et al., 2018). On the numerator, only polymer and base chemicals are considered as recycled products to conform to the definition of ‘recycling’ by the WFD (European Commission 2018a, 2008), which excludes materials (such as fuel) for energy usage. The *plastic-to-plastic rate* (P2P), *plastic-to-chemicals rate* (P2C), and *plastic-to-fuels rate* (P2F) (measured in%) are described as the share of total mass (in kt) of plastic waste generated

Table 2

Summary of circularity indicators of plastic waste treatment, their corresponding definitions and formulas applied in this study, which are also elaborated in previous studies (UNEP, 2011; Perio et al., 2018; Broeren et al., 2022; Arena and Ardolino, 2022).

Circularity indicators	Definition	Equation
<i>End-of-life recycling rates (EoL-RR)</i>	The total mass of plastic waste that is converted into secondary materials (polymers and base chemicals) over total plastic waste generation (i.e., reported plastic waste (in S0–S4) plus the ‘missing plastic’ (in S5) under the definition of ‘recycling’ from the European Commission (2018a, 2008), excluding plastic waste-to-energy (e.g., hydrocarbons)	$\text{EoL-RR} = \frac{\mu_{\text{polymer}} + \mu_{\text{base chemicals}}}{\mu_{\text{reported waste}}} \text{ (in S0–S4) (Eq. 1)}$ $\text{EoL-RR} = \frac{\mu_{\text{polymer}} + \mu_{\text{base chemicals}}}{\mu_{\text{reported waste}} + \mu_{\text{missing plastic}}} \text{ (in S5) (Eq. 2)}$
<i>Plastic-to-plastic rate (P2P)</i>	The total of plastic waste that is converted into new polymer over the total plastic waste generation	$\text{P2P} = \frac{\mu_{\text{polymer}}}{\mu_{\text{reported waste}}} \text{ (in S0–S4) (Eq. 3)}$ $\text{P2P} = \frac{\mu_{\text{polymer}}}{\mu_{\text{reported waste}} + \mu_{\text{missing plastic}}} \text{ (in S5) (Eq. 4)}$
<i>Plastic-to-chemicals rate (P2C)</i>	The total of plastic waste that is converted into base chemicals over the total plastic waste generation	$\text{P2C} = \frac{\mu_{\text{base chemicals}}}{\mu_{\text{reported waste}}} \text{ (in S0–S4) (Eq. 5)}$ $\text{P2C} = \frac{\mu_{\text{base chemicals}}}{\mu_{\text{reported waste}} + \mu_{\text{missing plastic}}} \text{ (in S5) (Eq. 6)}$
<i>Plastic-to-fuels rate (P2F)</i>	The total of plastic waste that is converted into fuels for energy use over the total plastic waste generation	$\text{P2F} = \frac{\mu_{\text{fuel}}}{\mu_{\text{reported waste}}} \text{ (in S0–S4) (Eq. 7)}$ $\text{P2F} = \frac{\mu_{\text{fuel}}}{\mu_{\text{reported waste}} + \mu_{\text{missing plastic}}} \text{ (in S5) (Eq. 8)}$

¹ The definition of ‘recycling’ as stated in European Commission (2018a, 2008) reports are ‘any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations’. Hence, it (mainly) includes plastic waste recycling back into plastic from mechanical recycling in 2018. When chemical recycling is implemented in 2030, ‘recycling’ can include plastic waste recycling back into plastic or other materials for other purposes (e.g., base chemicals from pyrolysis for petrochemical industry such as cosmetics, fertilizers, pharmaceutical, etc.), excluding fuel or energy use.

($\mu_{\text{waste generation}}$) that is converted into polymers (μ_{polymer}), base chemicals ($\mu_{\text{base chemicals}}$), and fuels (μ_{fuel}), respectively (Broeren et al., 2022; Arena and Ardolino, 2022). On the denominator, in S0–S5, only the reported plastic waste ($\mu_{\text{reported waste}}$) is considered and in S5 the reported plastic waste plus ‘missing plastic’ ($\mu_{\text{reported waste}} + \mu_{\text{missing plastic}}$) is considered (see Fig. 2). In all developed scenarios, the assumed legal waste export for recycling is not counted in the EoL-RR and P2P rate calculations.

2.5. Uncertainty analysis

The uncertainty analysis is calculated because of the diversity of the modeling inputs that are taken from relevant literature related to the waste management practices in EU 27+3 (Table S2–S6). The uncertainty analysis is calculated assuming TD of the input parameters (i.e., the TCs). As suggested by Bisinella et al. (2016), the uncertainty is calculated by systematically propagating the output uncertainties (i.e., mass of plastic flows and circularity indicators). For this, the Monte Carlo analysis with 1000 iterations is used to randomly sample a value within each uncertainty distribution and calculate the standard deviation, which is shown relative to the likely value in%. For example, if the MFA

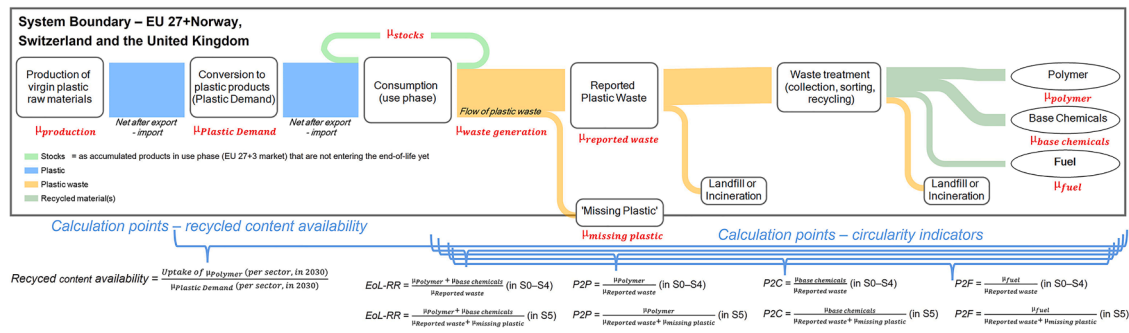


Fig. 2. Conceptual diagram of life cycle of plastic (adapted from Plastics Europe) (Plastics Europe, 2019a, 2019b) to show the calculation points for each circularity indicator and recycled content availability. The thickness of the flows does not represent mass/quantity. Abbreviation: EoL-RR (End-of-life recycling rate), P2C (plastic-to-chemicals), P2F (plastic-to-fuel), P2P (plastic-to-plastic).

result shows 4090 kt of polymer production with the uncertainty of ± 353 kt, the result is presented as $4090 \text{ kt} \pm 9\%$ (i.e., $353 \text{ kt} / 4090 \text{ kt} \times 100\%$). For the circularity indicators, if the EoL-RR is estimated to be 24% with $\pm 2\%$ uncertainty, it means that the likely values (i.e., 24%) can be deviated to 22% (min.) and 26% (max.). This approach is consistently applied throughout the MFA modeling in this study.

2.6. Estimation of the recycled content availability in 2030

From the MFA model results, the potential use of recycled plastic in different markets and applications is investigated. However, it is challenging to project future market uptake of recycled plastic production because of i) different quality of recycled plastic, ii) a breadth of technical requirements of various applications, and ii) market saturation of some applications (Demets et al., 2020; Huysveld et al., 2022; Tonini et al., 2022). In this study, two assumptions are considered to quantify the potential recycled plastic (in kt) and recycled content (in%) availability in 2030. First, projecting the share of market uptake of recycled plastics in 2018 reported by Watkins et al. (2020) and European Commission (2020) (details in Table S13). Second, assuming 100% closed-loop recycling, i.e., no mass exchange between the sectors. The closed-loop recycling itself is defined as the use of recycled materials for the same market applications as that of its previous life cycle (UNEP, 2011), e.g., recycled plastics from packaging waste is used in the same sector. This is perceived as ‘explorative’ projection, in a sense that it does not take into account for example quality aspects yet (e.g., technical properties, processability, color, etc.) because of the difficulty to predict future market uptake (incl. potential market share of the intended applications) and the quality of recycling (Huysveld et al., 2022; Tonini et al., 2022; Hestin et al., 2017) at the time of writing the manuscript. Thus, it should be seen as a maximum uptake under optimal conditions and it is likely that the actual uptake will be lower.

The recycled content (in%) is quantified as the share of the uptake of recycled plastic over the projected plastic demand per sector in 2030 (Eq. (9)). For this purpose, the plastic demand in 2030 is projected using linear regression from Plastics Europe (data from 2014 to 2020) (Plastics Europe, 2019a, 2019b) and is elaborated in Figure S28. It is important to note that the amount of plastic flowing from use phase to EoL phase ($\mu_{waste\ generation}$) in 2030 is not the same as the plastic demand in 2030 ($\mu_{plastic\ demand}$) because some plastic will remain in ‘stock’ (μ_{stocks}) depending on their lifespan distribution (Fig. 2), as described by Lase et al., (2021).

$$\text{Recycled content availability} = \frac{\text{Uptake of } \mu_{polymer} \text{ (per sector, in 2030)}}{\mu_{plastic\ demand} \text{ (per sector, in 2030)}} \times 100\% \quad (9)$$

3. Results

3.1. Material flow analysis: status quo (in 2018) and future scenarios (in 2030)

The MFA results of the ten polymers over the different sectors are shown in Figs. 3A–F for S0 – S5, respectively. Per sector, the Sankey diagrams can be found in Figures S29–S53, and the mass balances can be found in Table S15.

In the *status quo* scenario (S0), it is estimated that $3273 \pm 9\%$ kt of polymer (i.e., recycled plastic) is produced from plastic recycling systems in 2018, while $12,287 \pm 3\%$ kt plastic waste are sent for residual treatment and $1805 \pm 5\%$ kt are sent to waste export and/or informal treatment (e.g., illegal export or unauthorised recycling by brokers or scraps dealers) (Fig. 3A). According to the figures from Plastics Europe (Plastics Europe, 2019a, 2019b), it is estimated that 37% and 63% of the waste sent for residual treatment is landfilled and incinerated, respectively.

The results obtained for S1, assuming best practices of waste collection, sorting, and MR are widely applied in the whole EU 27+3, show that the recycled plastic production is expected to increase to $10,277 \pm 5\%$ kt (Fig. 3B), which is approx. 3.0 times higher than what is estimated for S0. Still, a considerable amount of plastic waste is sent to residual treatment (i.e., $10,253 \pm 5\%$ kt) and a small share is still sent to waste export and/or informal treatment ($402 \pm 10\%$ kt). From the results obtained for S2, which is the scenario in which CR and SBR have become dominant (i.e., CR and SBR technologically outcompetes MR), it can be observed that $7903 \pm 6\%$ kt of recycled plastic are produced together with $7247 \pm 6\%$ kt of base chemicals and $1189 \pm 4\%$ kt of fuel (Fig. 3C). The recycled plastic production in S2 (i.e., $7903 \pm 6\%$) is approx. 2.5 times higher than in S0. However, the recycled plastic production in S2 is slightly lower than in S1 (i.e., a reduction of approx. 23% of recycled plastic produced compared to S1), yet considerable amounts of base chemicals and fuels are produced in S2 as opposed to S1. Important to note is that these numbers are based on the Transfer Coefficients (TCs) retrieved from current data sources (see Table S7–S11), and, while potential improvements in the technology might still occur, it is nevertheless difficult to quantify technological learnings without an established history (as assumed for MR, sorting or collection rates).

In Fig. 3D and 3E, the MFA results display that $12,262 \pm 6\%$ kt and $12,740 \pm 6\%$ of recycled plastic are estimated to be produced from S3 (the scenario in which little competition between CR, SBR, and MR occurs) and S4 (the scenario in which CR serves as complementary technologies to MR), respectively. This shows that the implementation of MR, CR and SBR in treating plastic waste delivers a higher quantity of recycled plastic compared to S1 (which considers only improved MR) and S2 (which considers only CR and SBR). In particular, the MFA results for S4 estimate that CR produces $3110 \pm 6\%$ kt recycled plastic. This

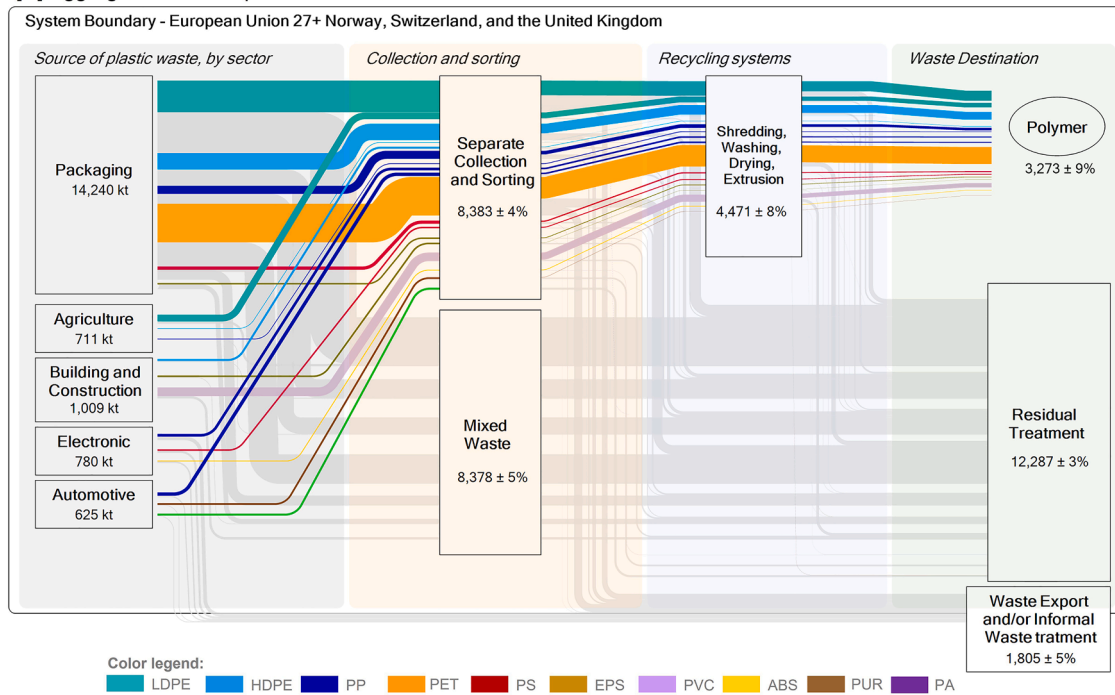
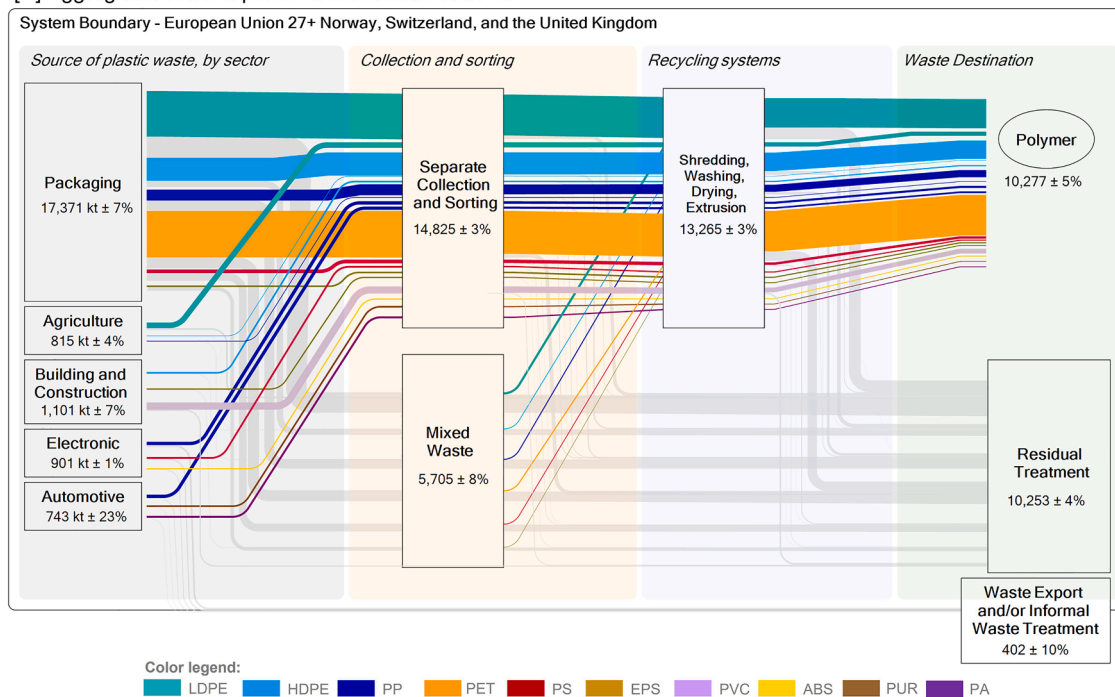
[A] Aggregated flows of plastic waste treatment in S0**[B] Aggregated flows of plastic waste treatment in S1**

Fig. 3. Material flow analysis of the selected polymers throughout the waste management systems in EU 27+3 in 2018 and 2030 of S0 (3A), S1 (3B), S2 (3C), S3 (3D), S4 (3E) and S5 (3F). Values are in rounded in kilo tonne, including the calculated standard deviation (in%). Different colors represent different polymer types, while the gray color refers to waste export and/or informal waste treatment (e.g., illegal export or unauthorised recycling brokers/scraps dealers), mixed waste, reject (from sorting, washing, extrusion), and residual streams. The dark green, light green, and dark brown colors represent (mixed) polymer, base chemicals, and fuel productions from chemical recycling, respectively.

finding aligns with [SYSTEMIQ \(2022\)](#) and [Caro et al., \(2022\)](#) that estimate around 3100 and 3400 kt P2P production from CR and SBR, respectively. On the other hand, in S3 and S4, the amount of base chemicals production from plastic waste treatment is estimated to be 4272 ± 6% kt and 3951 ± 6% kt (i.e., a reduction of 41% and 45% compared to S2, respectively), while the fuel production from the same

scenarios is estimated to be 683 ± 4% kt and 628 ± 4% kt, respectively. For S5 (the scenario in which extra mass from the 'missing plastic' is treated via CR and MR), the recycled plastic, base chemicals, and fuel production from plastic waste is estimated to be 18,536 ± 6% kt, 5556 ± 6% kt, and 881 ± 4% kt, respectively ([Fig. 3F](#)). The inclusion of the 'missing plastic' in future plastic waste recycling treatment, combined

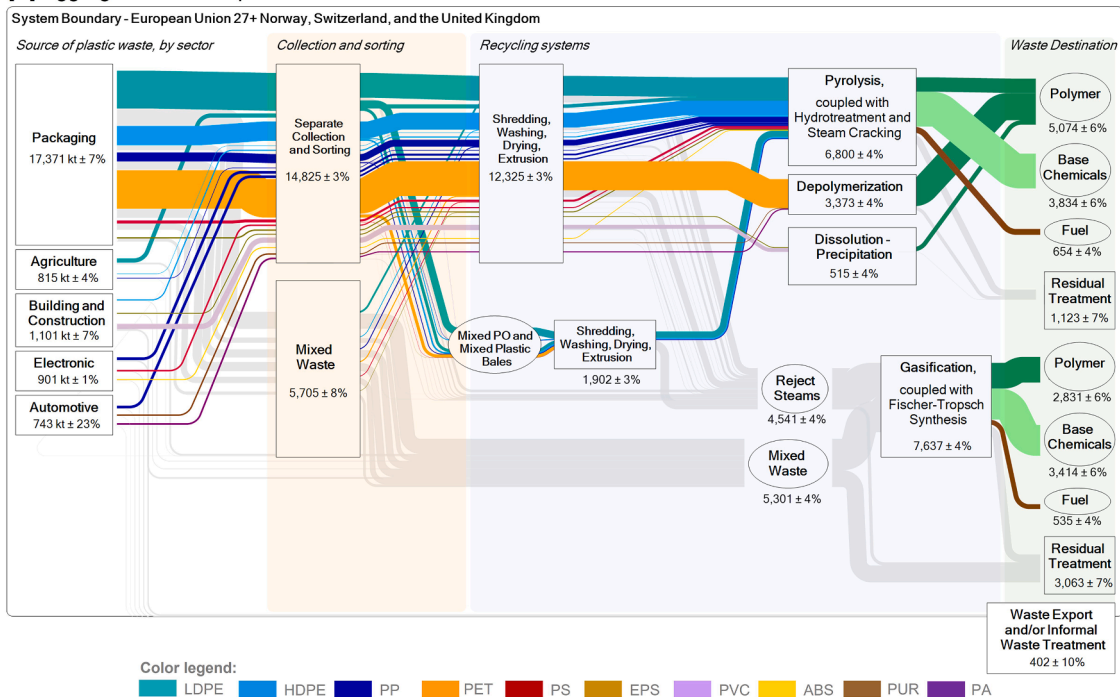
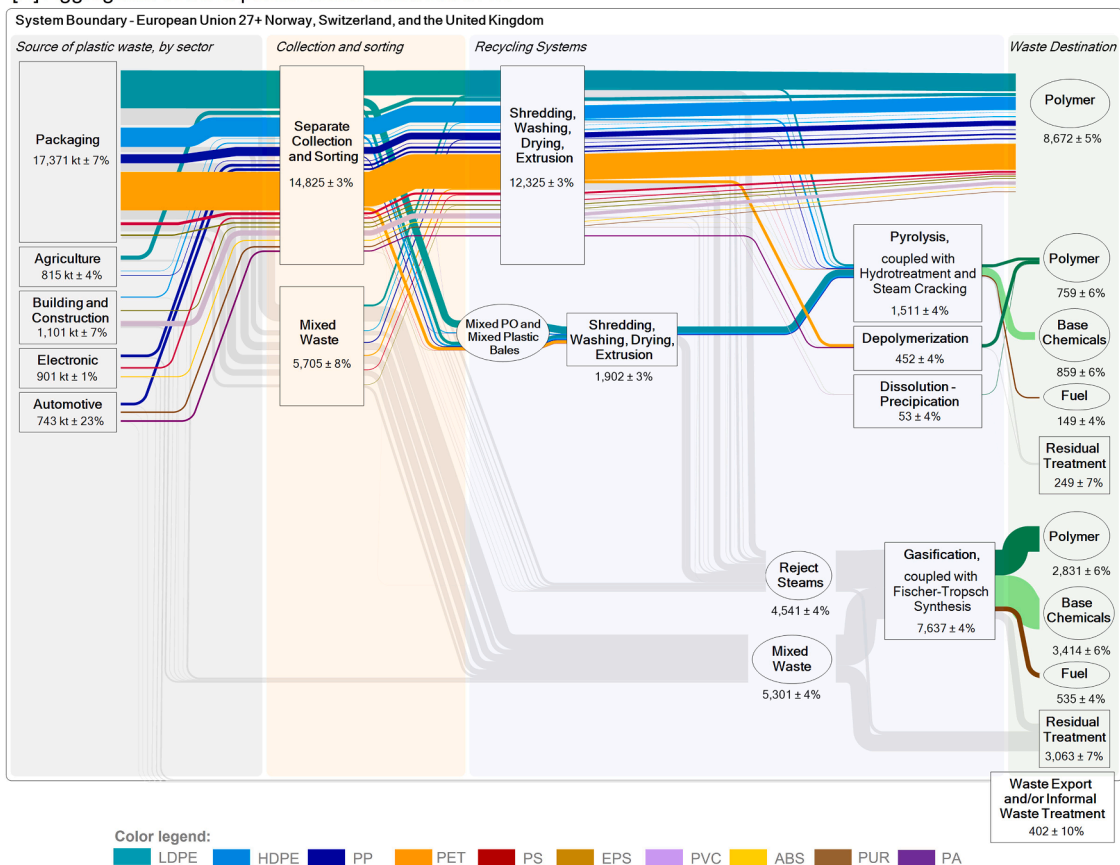
[C] Aggregated flows of plastic waste treatment in S2**[D] Aggregated flows of plastic waste treatment in S3**

Fig. 3. (continued).

with complementarity between MR and CR, increases the total recycled plastic production by 5.5 times relative to S0. This would allow reaching the recycled content target (Section 3.3).

3.2. Circularity of plastic value chain: to what extent can chemical recycling contribute to improve plastic recycling in EU?

Table 3 summarizes the results obtained for the circularity indicators

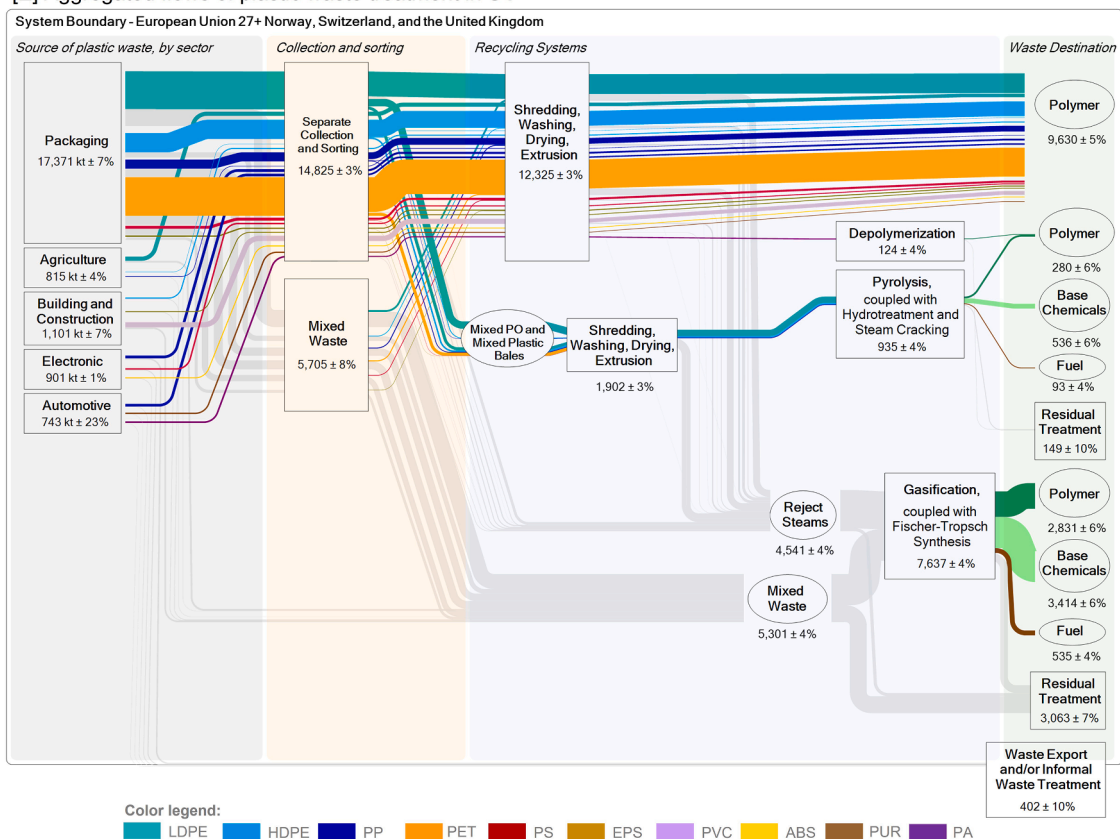
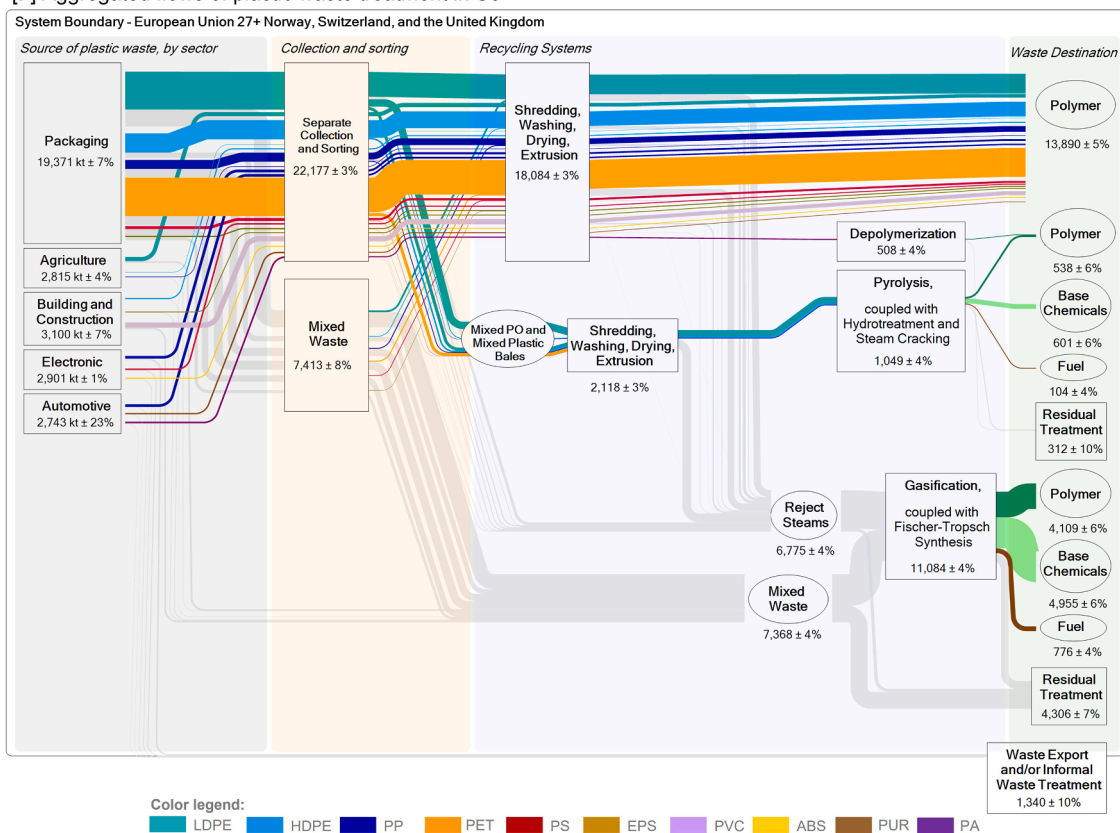
[E] Aggregated flows of plastic waste treatment in S4**[F] Aggregated flows of plastic waste treatment in S5**

Fig. 3. (continued).

Table 3

Summary of the circularity indicators for all scenarios in 2018 (S0) and 2030 (S1–S5). Values are rounded, including the standard deviation (in%). Acronyms: CR (chemical recycling), EoL-RR (end-of-life recycling rate), MR (mechanical recycling), P2C (plastic-to-chemical), P2F (plastic-to-fuel), P2P (plastic-to-plastic), SBR (solvent-based recycling).

¹ Overall circularity indicators	S0	S1	S2	S3	S4	S5
P2P	18% ± 2%	49% ± 3%	38% ± 2%	58% ± 3%	61% ± 3%	61% ± 3%
P2P from MR	18% ± 2%	49% ± 3%	–	41% ± 3%	46% ± 3%	46% ± 3%
P2P from CR and SBR	–	–	38% ± 2%	17% ± 1%	15% ± 1%	15% ± 1%
P2C	–	–	35% ± 2%	20% ± 1%	19% ± 1%	19% ± 1%
P2F	–	–	6% ± 0%	3% ± 0%	3% ± 0%	3% ± 0%
² EoL-RR	18% ± 2%	49% ± 3%	73% ± 3%	78% ± 3%	80% ± 3%	80% ± 3%

¹ The 'overall' data points quantify the sum of mass quantities (in kt) from all sectors and aggregated calculations for the circularity indicators.

² EoL-RR considers only P2P and P2C because P2F recycling does not conform to the definition of 'recycling' in WFD (European Commission, 2018a, 2008).

(EoL-RR, P2P, P2C, and P2F rates) for scenarios S0 – S5. The EoL-RR of plastic waste in S0 is 18% ± 2% in which the only contributor is P2P from MR. Significant improvements in the EoL-RR can be observed in all future scenarios (S1 – S5). The overall EoL-RR in S1 (i.e., 49% ± 3%) is approx. 2.7 times higher than in S0 (i.e., 18% ± 2%). For the S2, the EoL-RR (i.e., 73% ± 3%) is approx. 4 times higher than in S0 and it is approx. 1.5 times higher than in S1. In S2, 38% ± 2% and 35% ± 2% of the overall EoL-RR come from P2P and P2C from CR and SBR (only P2P), respectively. However the P2P rate in S2 (38% ± 2%) is slightly lower than the P2P rate in S1 (49% ± 3%) (Table 3).

The results of circularity indicators for S3 and S4 estimate that the overall EoL-RR increases by approx. 4.5 times higher relative to S0 (Table 3). When comparing to S1, the EoL-RR of S3 and S4 (i.e., 78–80% ± 3%) is 1.6 times higher, while when comparing to S2, the EoL-RR of S3 and S4 is 1.1 times higher. It is estimated that the EoL-RR in S3 and S4 comes from P2P from MR (41–46% ± 3%), P2P from CR and SBR (15–17% ± 1%), and P2C from CR (19–20% ± 1%). When the 'missing plastic' is included in S5, the EoL-RR is identical to S4 however S5 produces more recycled plastics, base chemicals, and fuels as elaborated in the previous section (Section 3.1). It is important to note that in this study the EoL-RR is calculated as the share of total recycled plastic (and base chemicals) over waste generated (incl. 'missing plastic' in S5) hence resulting the same EoL-RR in S4 and S5, but with different quantities involved. Furthermore, in all scenarios where CR options are implemented, the P2F rate is relatively low ranging from 3% (S3–S5) to 6% (S2).

In Table S16 the plastic circularity per sector can be found. In *status quo* scenario (S0) the highest EoL-RR is achieved by agriculture sector (44% ± 5%), followed by building and construction (30% ± 2%), packaging (17% ± 2%), electronic (17% ± 2%), and automotive sectors (10% ± 1%), which is comparable with Maury et al., (2022) study. In all future scenarios (S1–S5), the EoL-RR will increase. In the most positive future scenarios (S4 and S5) the highest EoL-RR is achieved by building and construction and agriculture sectors (84% ± 5%), followed by packaging sector (81% ± 3%), automotive (72% ± 4%), and electronic sectors (60% ± 3%). CR and SBR implementation contribute in increased EoL-RR in future scenarios by adding around 15–18% ± 2% of P2C and 8–25% ± 2% of P2P from CR and SBR, while P2P from MR contributes 29–56% ± 3% (Table S16). Relative to S0, improved MR, CR and SBR implementation can increase the EoL-RR by roughly 2–5 times.

When focusing only on the P2P rate, the highest improvements can be observed in S4 and S5 (61% ± 3%). Moreover, the results suggest that

the smallest improvement in P2P rate (compared to the S0 *status quo*, 18% ± 2% P2P rate) is observed for S2 (i.e., 38% ± 2%) where all the sorted plastic waste, including the rejects (from sorting and MR) and mixed waste streams, are sent to CR options. The result obtained for S2 (CR and SBR become more dominant than MR) is lower than what is obtained for S1 (i.e., 49% ± 3%) where all sorted plastic waste is treated via MR (and CR and SBR are assumed zero).

3.3. Recycled content availability in 2030

Figs. 4 and 5 summarize the potential recycled plastic (i.e., only P2P from MR, CR, and SBR) and recycled content (RC) availabilities in 2030 per sector. Fig. 4 shows the results assuming that the share of recycled plastic uptake between sectors in 2018 is maintained in 2030 (i.e., closed-loop and open-loop recycling occur). For example, recycled plastic from plastic waste in packaging sector can be used for applications in packaging and other sectors too. In contrast, Fig. 5 shows the results assuming 100% closed-loop recycling (i.e., the recycled plastic is used in the same sector where the waste is originated). For example in Fig. 4A, it is estimated that the packaging sector will demand 22,057 kt of plastic (blue bar) in 2030 and it is estimated that 2817 kt of recycled plastic (green bar, in S1) will be produced, result in 13% RC availability (red dot, S1 in Fig. 4A). In Fig. 5A, assuming 100% closed-loop recycling based on best practices in MR, it is estimated that 8528 kt of recycled plastic could be produced in S1 and will thus result in a potential RC availability of 39% in packaging sector. In Fig. 4, the 'others' sector refer to household goods, furniture, textiles, sports equipment, etc.

From Fig. 4 it can be observed for all future scenarios (S1–S5) a considerable amount of recycled plastic is diverted into 'others' sector (3670–7141 kt) and make the RC availability for 'others' sector the highest among other sectors (from 39% in S2 to 77% in S5). The building and construction sector comes second as the biggest recycled plastic receiver (from 1986 kt in S2 to 5229 kt in S5), followed by the packaging sector (from 1318 kt in S2 to 3960 kt in S5). These result to RC availability ranges from 17% in S2 to 46% in S5 for building and construction sector, while the RC availability in packaging sector ranges from 6% in S2 to 18% in S5. The recycled plastic availabilities in the automotive (from 656 kt in S2 to 857 kt in S5), electronic (from 170 kt in S2 to 415 kt in S5), and agriculture sectors (from 107 kt in S2 to 936 kt in S5) are considerably lower than the packaging, construction and 'others' sector. These result in a considerably lower RC availability in automotive sector (6–15%) and electronic sector (3–11%). Again, note that all these results assume that the share of recycled plastic uptake between sectors in 2018 will be maintained in 2030.

When 100% closed-loop recycling is assumed (Fig. 5), the packaging sector is expected to receive the highest amount of recycled plastics (i.e., 7698–11,430 kt), as expected, followed by the building and construction sector (i.e., 619–2107 kt) since most of the recycled plastics are produced from these sectors (see Table SI15). The highest increase of RC availability can be observed in the packaging and electronic sectors (i.e., 3.5 times higher than assumed 2018 market uptake) and the lowest increase in the automotive sector (i.e., 1.5 times higher than assumed 2018 market uptake). As results, the RC availability increases to 35–52% in packaging sector and 5–38% in electronic sector. Still, in the automotive sector the RC availability increases to 5–26% (Fig. 5). Instead, as expected, the potential RC availability in the construction sector is 2.5 lower than if current trends are maintained (open- and closed-loop, Fig. 4), which reduces the RC availability to 5–19%.

4. Discussion

4.1. Interpretation and contextualization of the results in relation to other studies

The MFA results of the *status quo* scenario (S0, 3273 ± 9% kt) obtained in this study is comparable to the findings of Watkins et al.,

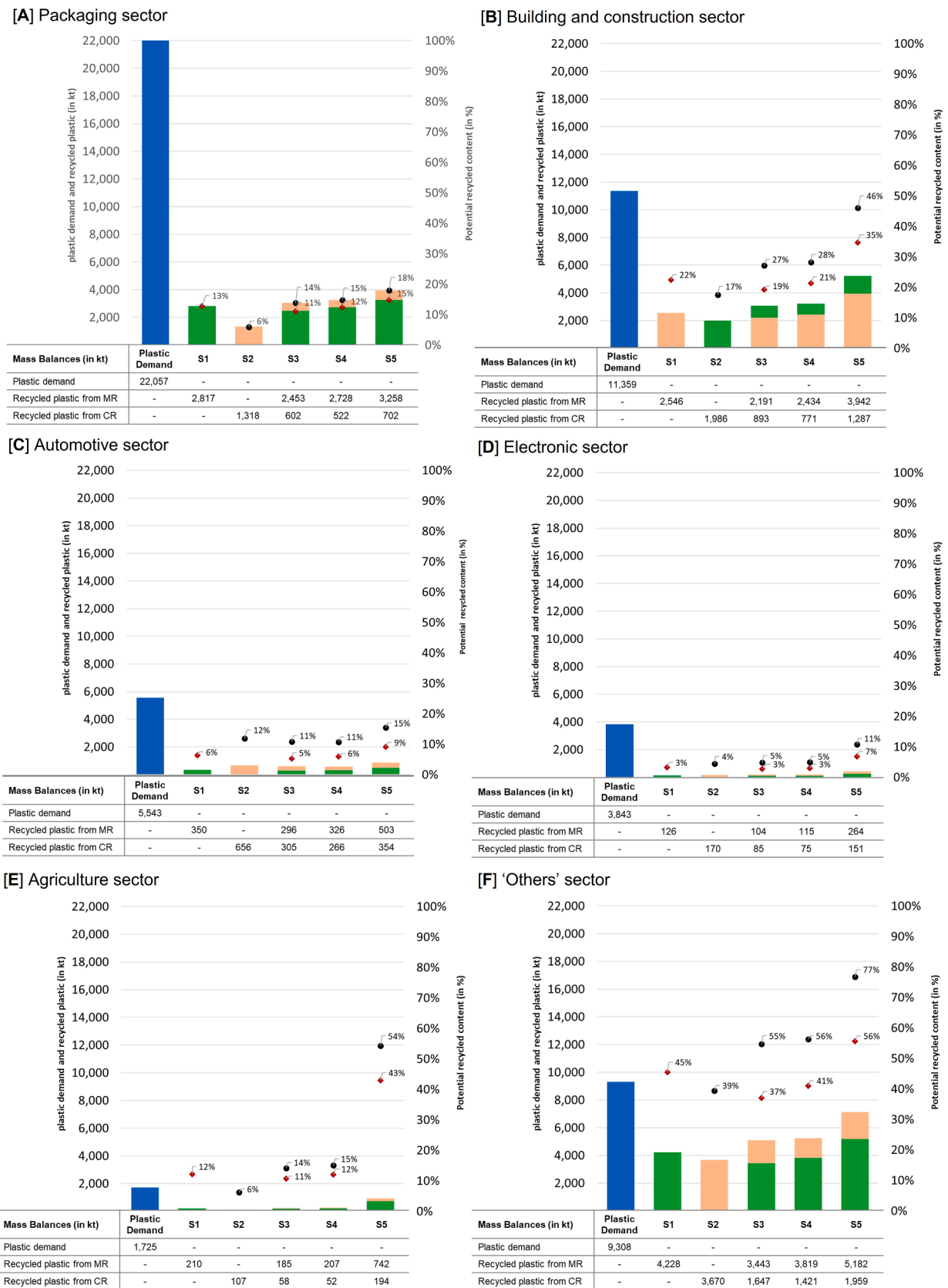
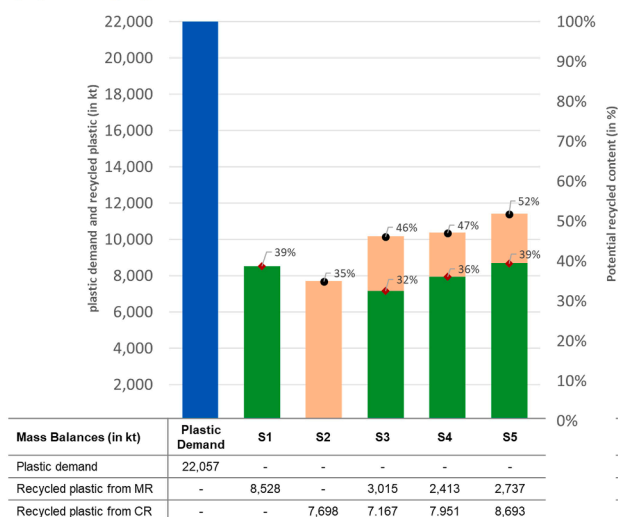
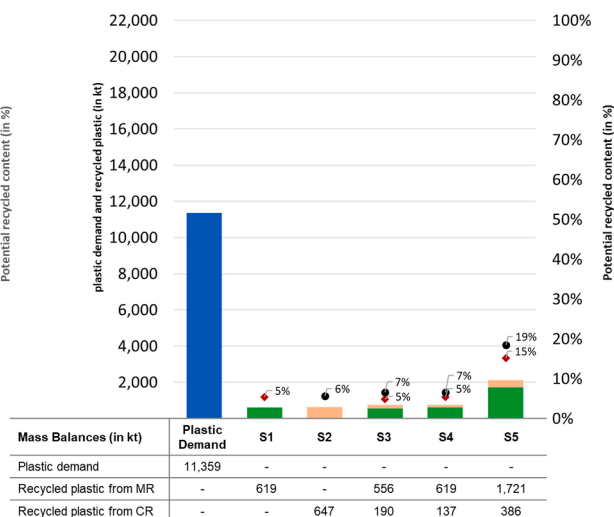


Fig. 4. Projected plastic demand (blue bar, in kt), recycled plastics production from mechanical recycling (green bar, in kt) and chemical recycling (orange bar, in kt), and recycled content (the dots, in%) assuming recycled plastic market uptake in 2018 based on [Watkins et al., \(2020\)](#) and [European Commission \(2020\)](#). The red dot represents the potential recycled content achieved via mechanical recycling. The black dot represent potential recycled content achieved via chemical recycling or the sum of mechanical recycling and chemical recycling.

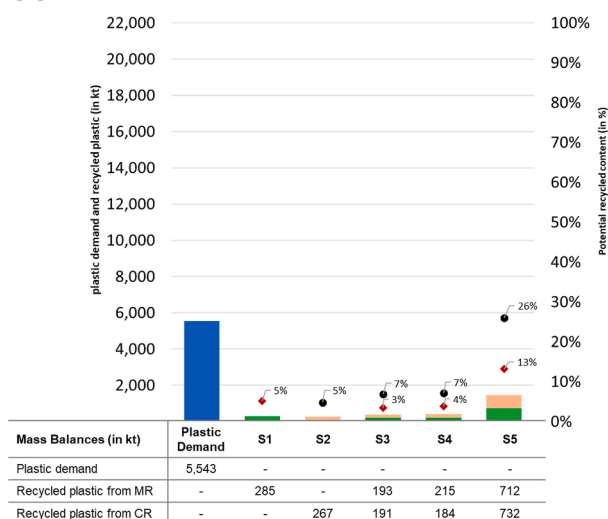
[A] Packaging sector



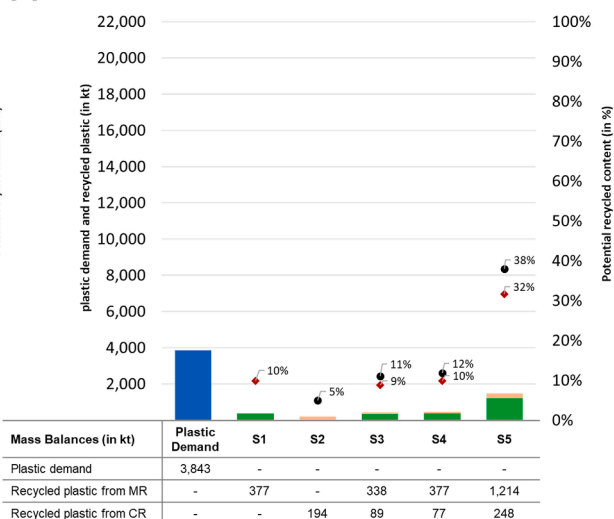
[B] Building and construction sector



[C] Automotive sector



[D] Electronic sector



[E] Agriculture sector

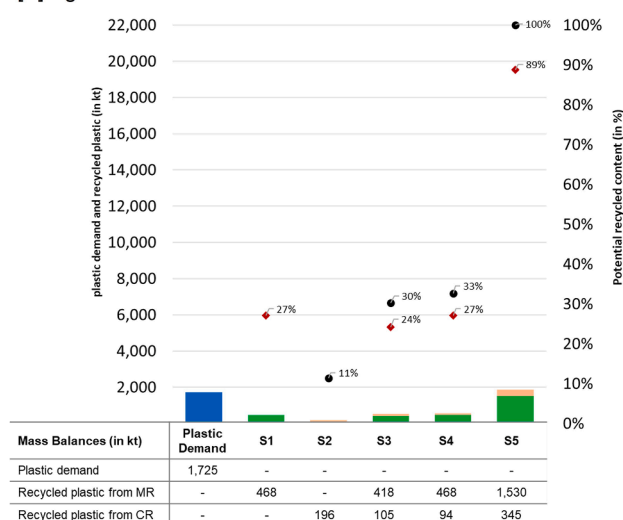


Fig. 5. Projected plastic demand (blue bar, in kt), recycled plastics production from mechanical recycling (green bar, in kt) and chemical recycling (orange bar, in kt), and recycled content (the dots, in%) assuming 100% closed-loop recycling. The red dot represents the potential recycled content achieved via mechanical recycling. The black dot represent potential recycled content achieved via chemical recycling or the sum of mechanical recycling and chemical recycling.

(2020) (i.e., 3854 kt of recycled plastic in 2018). [Plastics Europe \(2020\)](#) instead estimated a higher amount of recycled plastic, i.e., around 4900 kt in 2018, likely due to the higher number of polymer types considered. In S0 (*status quo* scenario), the total amount of waste export and/or informal waste treatments ($1805 \pm 5\%$ kt) is comparable to [Plastics Europe \(2020\)](#) and [Eurostat \(2022d\)](#) data, which indicate a total export of 1900 kt and 1593 kt in 2018, respectively. Several studies have shown that plastic waste can be legally or illegally exported to countries like Turkey, Malaysia, Vietnam, Ghana, Nigeria, Argentina, etc. ([Tran, 2018](#); [Wang, 2014](#); [Liang et al., 2021](#); [Petrlik et al., 2019](#); [Chen et al., 2021](#)). Note that in this study the exported waste is neither counted as recycling (i.e., not contributing to the EoL-RR) nor considered in the calculation of recycled content availability in EU27+3. The exact fate of the currently shipped waste, evolution of export quantities, and final geographical and technical destination should be subjected to future research.

Looking at each future scenario in 2030 (S1–S5), including when the CR and SBR are implemented, it can be observed that the recycled plastic produced from only CR and SBR implementation (S2; $7903 \pm 6\%$ kt) is considerably lower than the other developed scenarios in this study (i.e., S1, S3, S4, S5). This also means that the highest recycled plastic production possible can be achieved only when MR, CR and SBR are implemented simultaneously, as can be observed in the other investigated future scenarios in 2030.

Focusing on the circularity indicators, it can be observed that modeling results of EoL-RR in 2018 ($18\% \pm 2\%$) is lower than the one reported by [Plastics Europe \(2019a, 2019b\)](#) (i.e., 33%) but higher than the one reported by [Material Economics \(2022\)](#) and [Agora Industry \(2022\)](#), which is 15%. Important aspects to consider when comparing these numbers are i) recycling rate measurement points (as numerator in the EoL-RR formula) and ii) total considered EoL plastic waste (as denominator in the EoL-RR formula). The reported EoL-RR from [Plastics Europe \(2019a, 2019b\)](#) (i.e., 33% EoL-RR) calculates the share of sorted plastic waste that is sent to recycling facilities (9.6 Mt as the numerator) over the reported waste quantities (29.1 Mt as the denominator), which increases the EoL-RR. The reported EoL-RR by [Plastics Europe \(2019a, 2019b\)](#) further excludes the ‘missing plastic’ (i.e., 8–15 Mt) and, to a large extent, the losses from recycling, which inclusion will decrease further the EoL-RR. On the other hand, EoL-RR calculation by [Material Economics \(2022\)](#) and [Agora Industry \(2022\)](#) (i.e., 15% EoL-RR) consider the net recycled plastic production (6.7 Mt, after extrusion and losses from recycling) as the numerator and reported plastic waste generated plus the ‘missing plastic’ as the denominator (i.e., estimated to be 45 Mt). In this study the EoL-RR is calculated based on the share of total recycled plastic production (plus base chemicals when CR is implemented) over the total plastic waste generation (incl. the ‘missing plastic’ in S5) (see [Table 2](#)).

4.2. Potential contribution of chemical recycling to plastic recycling rates

Mass balance approach, as shown in this study, has been proposed to measure the contribution of CR and SBR ([Broeren et al., 2022](#)). For CR technologies, for example pyrolysis, the mass balance approach means accounting for the full process from breaking down the polymer chains into its basic building blocks (e.g., pyrolysis oil), purification steps (e.g., distillation and hydrotreatment), feeding into cracking process (e.g., steam crackers) to produce base chemicals (incl. olefins), and (re)polymerization ([Tabrizi et al., 2021](#)). Moreover, the mass balance approach can also be used as a tool by policy makers to monitor the yield of CR and SBR technologies and to formulate ambitious but realistic recycling targets (e.g., EoL-RR targets for plastic).

As CR options yield multiple products (i.e., monomers, chemicals, and hydrocarbon), it is important to clearly identify the potential quantities of each output to further distinguish recycled plastic production (i.e., plastic-to-plastic recycling) from the other outputs (e.g., plastic-to-fuel). This is also relevant to appropriately report the plastic recycling rate in Europe to monitoring the attainment of recycling

targets, since the production of fuels (i.e., recycling products to be used as energy sources such as hydrocarbons) is not considered as ‘recycling’ under the Waste Framework Directive (WFD) ([European Commission, 2018a, 2008](#)). In this context, this study strives to differentiate between multiple outputs from CR (i.e., polymer, base chemicals, and fuel) in the endeavor to better illustrate the potential contributions of CR technologies to plastic circularity and recycling rates. Moreover, it is important to highlight that in all future scenarios in which CR options for plastic waste treatment are considered, the base chemicals production refers to producing valuable materials (e.g., wax, benzene, toluene, xylene, methane, propane, etc.) as suggested by previous studies ([Civancik-Uslu et al., 2021](#); [Kusenberget al., 2022a](#); [Kusenberget al., 2022b](#); [Kusenberget al., 2022c](#); [Ghalomi et al., 2021](#); [Zayoud et al., 2022](#)), which might be used as feedstock in the petrochemical industries. Moreover, the fuel is mainly hydrocarbons (gas and oil), which can also be used as energy input for CR processes ([Civancik-Uslu et al., 2021](#); [Larrain et al., 2020](#)).

By observing the circularity indicators in all future scenarios (S1–S5), it can be noticed the most positive scenario with EoL-RR of $80\% \pm 3\%$ is achieved when MR and CR are implemented simultaneously and complementarily, as opposed to only improving MR (S1, EoL-RR $49\% \pm 3\%$) or CR and SBR (S2, EoL-RR $73\% \pm 3\%$). The highest EoL-RR ($80\% \pm 3\%$) is indeed achieved in S4 and S5. In these two scenarios, the EoL-RR reaches $80\% \pm 3\%$ because of the contribution of improved MR ($46\% \pm 3\%$) and complementary CR ($34\% \pm 1\%$), where, out of the total obtained, $15\% \pm 1\%$ is related to the P2P rate and $19\% \pm 1\%$ to the P2C rate. These findings illustrate the importance of balancing the plastic waste streams into MR and CR options to reach the highest circularity potential possible, i.e. the two technologies need to be complementary and not competitive. It should also keep in mind that, in future scenarios, CR might be able to increase its P2P ratio (at the cost of P2C and P2F), for example by applying other pyrolysis conditions such as by adding catalysts, hydrocracking, etc. ([Kusenberget al., 2022e](#); [Kusenberget al., 2022a](#)). A study from [Eschenbacher et al. \(2022\)](#) suggests that the yield of olefins (i.e., C2–C4) from a mixed polyolefin waste can increase up to $\sim 75\%$ by introducing catalysts. Thus, for example, if the yield of naphtha can improve, the P2P rate can increase by up to $\sim 65\%$ (given the same yield from naphtha to monomers in the steam crackers).

By examining circularity indicators per sector, it can be observed that CR implementation contributes to reach recycling targets. In the packaging sector, the recycling targets stated by PPWD (i.e., 55% by 2030, [European Commission, 2018](#)) cannot be achieved only by improving the current waste management treatments (i.e., collection, sorting, and MR) as the estimated EoL-RR in S1 is $49\% \pm 3\%$. The CR and SBR options will contribute to reach the recycling targets set by PPWD, as the EoL-RR is expected to increase to $73\% \pm 4\%$, $80\% \pm 3\%$, $81\% \pm 3\%$, and $81\% \pm 3\%$ in S2, S3, S4, S5, respectively. The P2P and P2C from CR and SBR is estimated to add $15\text{--}38\% \pm 2\%$ and $20\text{--}35\% \pm 2\%$ to the EoL-RR in packaging sector (i.e., $73\text{--}81\% \pm 3\%$) in S2–S5, respectively. The contribution of CR and SBR options to increase the EoL-RR can also be noticed in the other sectors, e.g., significant improvements in the EoL-RR in the automotive sector are expected (from $38\% \pm 3\%$ in S1 to $72\% \pm 4\%$ in S4 and S5, [Table SI16](#)). Furthermore, the findings from this study (in [Table SI16](#)) can also be used as the basis to formulate recycling targets for plastic waste in the sector with no targets yet (e.g., in agriculture or construction sector).

In a similar way, the results can be used to perform plausibility-checks on stakeholders’ pledges. For example, it can be observed that the recycled plastic produced from only CR and SBR of plastic (S2; $7903 \pm 6\%$ kt) is not enough to meet the pledges made by CPA to reach 10,000 kt in 2030 ([European Commission, 2022a](#)). It is evident that such goal can only be achieved with an important contribution by MR, CR and SBR (as in scenario S3, S4, and S5)

4.3. Plausibility-checks on achievable recycled content targets

Mass balance approach has been proposed to monitor and determine recycled content of a product (Broeren et al., 2022; Tabrizi et al., 2021). For consumers, the mass balance approach means that brands and product manufacturers should ensure full transparency of the claimed recycled content (e.g., share of recycled plastic) of the total weight of a product. Policy makers can use mass balance approach can be used to measure recycled content targets via, for example, transparent monitoring and certification systems (Tabrizi et al., 2021). Moreover, the presented MFA model (using mass balance principles) can support policy makers to formulate ambitious but realistic recycled content targets (for plastic-based items) by taking into account the quantities of recycled plastic produced annually. This MFA model can also be used to identify the bottlenecks towards meeting the targets.

Looking at the RC availability per sector, it can be observed that a significant amount of recycled plastic (i.e., 3670–7141 kt) might be used in the ‘others’ sector (i.e., household goods, textile, etc.) as open-loop recycling in 2030. In other words, if the current market uptake as of 2018 is maintained in 2030, the pledges or targets on RC in some sectors such as automotive and electronic will not be achieved. For example, 25–30% RC target in electronic sector (Sandoval, 2018; Lase et al., 2021) will not be met as only 11% of RC would be available at the most positive scenario (i.e., CR is implemented and ‘missing plastic’ is accounted for, S5 in Fig. 4D). Similarly, the RC targets in automotive sector (i.e., 20–25% in new passenger cars; Maury et al., 2022; Volvo, 2018) is not achieved as only 15% RC will be available in the most positive scenario (S5 in Fig. 4C). For electronic and automotive sectors, the RC targets can only be achieved by the inclusion of CR options, processing the ‘missing plastic’, and closed-loop recycling (S5 in Fig. 5C and 5D).

The findings on RC availability can be used to formulate targets for the each sector, e.g., packaging. It can be observed that around 35–52% of RC will be available for packaging sector in 2030, assuming closed-loop recycling (i.e., S1–S5 in Fig. 3A). This finding aligns with 30% RC targets for PET beverage bottles stated by the Single Use Plastic Directive (European Commission, 2019) as well as study from Bashirgonbadi et al. (2022) that shows PP films can be made of 32 wt% recycled PP. Therefore, the findings of this research can also be used as basis to set RC targets for broader plastic packaging types such as flexible packaging, HDPE bottles, etc.

4.4. Limitations of the study and future perspectives

This study focuses on the projected plastic flows and treatments in 2030 compared to the *status quo* in 2018. The projected plastic flows assumes that waste quantities will increase in 2030 based on a historical regression (more in the SI–Section 8). Using this approach, the implications of production and use-oriented solutions such as waste reduction, re-use or refill strategies (e.g., as stated in the proposal of Packaging and Packaging Waste Regulations; European Commission, 2022b) are yet to be evaluated in further research. Moreover, to achieve highest RC availability, one should take into account not only the mass flows (as shown in this study) but also the recycled plastic’s qualities suitable for certain applications. Addressing the quality of recycled plastic would improve the potential market applications recycled plastic. For example, there is a possibility that a considerable amount of mechanically-recycled plastic have to be exported outside EU 27+3 because the market that can deal with certain mechanical recycling qualities gets saturated (Grant et al., 2020), which would mean that certain quantities of recycled plastic produced in S1, S3, S4, and S5 (Figs. 3, 4, and 5) might not be used in the EU 27+3. According to the current perception, potential market applications that can use recycled plastic might be less of a concern for chemically-recycled plastic because of a higher quality (Manzuch et al., 2021; Huysveld et al., 2022).

To further improve the capabilities of the developed MFA model, a

more robust investigation should be carried out by taking into consideration not only the waste streams’ characteristics but also the quality of the secondary products to better understand their potential market applications. Evaluation of quality includes legal aspects to use recycled plastics in certain application (e.g., as food contact material), technical characteristics of recycled plastic to meet market specification (e.g., processability of recycled plastics), and consider potential market uptake (i.e., to avoid market saturation that will reduce the uptake of recycled plastic) (Huysveld et al., 2022; Tonini et al., 2022). A study from De Tandt et al. (2021) illustrates the importance to consider legislative requirements for the use of mechanical recycled plastic especially as food contact material. Studies from Demets et al. (2020) also show the complexity in defining quality of recycling that, to some extent, determines the uptake of recycled plastic produced.

Moreover, it is difficult to predict the market uptake of recycled plastic in the future as well as to realize RC targets. Nonetheless, the finding from this study can be used as basis to formulate realistically achievable targets or pledges regarding RC in new products in the near future, specifically by considering the current and potential future flows of recycled plastic. Lastly, the quantification of recycled content availability only shows the potential at sector level. However, some pledges are very specific to application or product level such as recycled content in electronic products (e.g., RC in coffee machines or vacuum cleaners). In this case, the findings can be perceived as indications or proxy towards the average recycled content availability in the respective sector and a more detailed research should be carried out to assess the feasibility of recycled content targets at application or product level. Ultimately, this study is limited to the selected ten polymers and six scenarios, which can be further extended in the future (based on new technological development and insights) alongside the quantification of the environmental and economic impact of the future plastic recycling scenario. The MFA model can be used as basis for analysis of the sustainability performance of different alternative scenarios towards meeting the circular economy targets (i.e., by coupling MFA with social-economic-environment impact assessment). More importantly, future research should aims to provide information on the sustainability aspects (e.g., social, economic, and environmental impacts) concerning CR. To date, several studies have indicated that the environmental performance of CR is better than landfill and incineration (Vollmer et al., 2020; Schwarz et al., 2021), but not outcompeting mechanical recycling. Yet, depending on the substitution rate of virgin plastic (i.e., the quality aspects), CR can perform better than mechanical recycling (i.e., 1:1 substitution rate of virgin plastic) (Huysveld et al., 2022). Thus, there is a need to further deal with quality aspects in such sustainability studies, for example also to take into account the other products from CR such as waxes or aromatics.

5. Conclusion

Current end-of-life recycling rate from 2018 data in Europe, based on mechanical recycling, is about 18% calculated from the amount of recycled plastic production over the reported plastic waste generation. The growth of plastic waste generation until 2030 is projected using historical data, while widespread implementation of production and use-oriented solutions such as waste reduction, re-use, re-fill, etc. are not yet considered in this study. In future, several scenarios can be deployed to improve the recycling rate. In first instance, stretching the possibilities of current commercially used mechanical recycling technologies can lead to an overall end-of-life recycling rate up to 49% in 2030. Results of this study show that the implementation of chemical and solvent-based recycling technologies bring positive impacts towards the end-of-life-recycling rate as plastic-to-plastic and plastic-to-chemicals recycling (from chemical recycling) will increase the rate up to 80%. In this most positive scenario (and potentially the most realistic one), chemical recycling becomes complementary (and not competitive) to improved mechanical recycling. In this scenario, plastic-to-plastic rate

of 61% can be achieved (46% from mechanical recycling and 15% from chemical recycling), with an additional plastic-to-chemical rate of 19%. In all cases, plastic-to-fuel rates range from 3% to 6%, but it will likely be reduced in the future in favor for polymer and chemical production. Moreover, the findings from this research suggest that the recycled content targets are achieved when closed-loop, chemical and solvent-based recycling, and processing 'missing plastic' are all simultaneously accounted for in plastic waste treatment. Capturing and treating the 'missing plastic' can significantly increase the recycled plastic production and this contribution appears necessary to be able to reach the recycled content targets in some sectors (i.e., 25–30% recycled content targets in new electronic products in 2030). For policy makers, the approach (i.e., mass balance model) and findings of this paper can also be used to support proposals of realistically achievable recycled content targets and support which recycling technologies can play which role(s) in achieving the targets.

Disclaimer

The views expressed in the article are the sole responsibility of the authors and in no way represent the view of the European Commission and its service.

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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. The views expressed in the article are the sole responsibility of the authors and in no way represent the view of the European Commission and its services.

Data availability

No data was used for the research described in the article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.resconrec.2023.106916](https://doi.org/10.1016/j.resconrec.2023.106916).

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