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Dynamic Material Flow Analysis of PET, PE, and PP Flows in Europe: Evaluation of the Potential for Circular Economy

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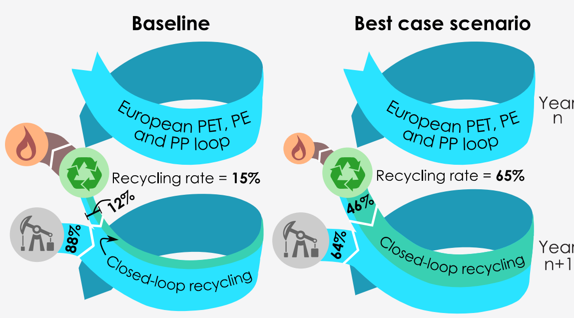
ABSTRACT: This study evaluates the potential circularity of PET, PE, and PP flows in Europe based on dynamic material flow analysis (MFA), considering product lifetimes, demand growth rates, and quality reductions of recycled plastic (downcycling). The circularity was evaluated on a baseline scenario, representing 2016 conditions, and on prospective scenarios representing key circularity enhancing initiatives, including (i) maintaining constant plastic consumption, (ii) managing waste plastic exports in the EU, (iii) design-for-recycling initiatives, (iv) improved collection, and (v) improved recovery and reprocessing. Low recycling rates (*RR*, 13−20%) and dependence on virgin plastic, representing 85−90% of the annual plastic demand, were demonstrated after 50 years in the baseline. Limited improvements were related to the individual scenarios, insufficient to meet existing recycling targets. However, by combining initiatives, RRs above 55%, where 75−90% was recycled in a closed loop, were demonstrated. Moreover, 40−65% of the annual demand could potentially be covered by recycled plastic. Maintaining a constant plastic demand over time was crucial in order to reduce the absolute dependence on virgin plastic, which was not reflected by the *RR*. Thus, focusing strictly on RRs and even whether and to which extent virgin material is substituted, is insufficient for evaluating the transition toward circularity, which cannot be achieved by technology improvements alone—the demand must also be stabilized.



1. INTRODUCTION

Plastic is one of the most common materials, made predominantly from fossil fuels,[1] with global annual production exceeding 300 Mt.[2] Despite many desirable properties, plastic is associated with several environmental concerns, including the release of fossil CO_2 upon incineration and overall dependence on fossil resources.[3]

To mitigate such challenges, the circular economy concept, where materials are recirculated into society, ultimately eliminating the need for virgin materials, has gained popularity, especially in the European Union (EU). Here, plastic has been identified as a priority material to decrease dependence on fossil resources.[4] However, almost 70% of the collected plastic waste in the EU is currently incinerated, landfilled, or exported to other countries.[5] To foster reutilization, the EU has adopted a target of 55% recycling by 2030 for household plastic packaging waste,[6] supplemented by voluntary commitments by the European plastic industry to recycle 70% (plastic packaging) and 50% (plastic waste) by 2040.[7] Despite political ambitions for high levels of plastic recycling exist, the insights into tangible potential solutions for individual regulatory measures to reach these ambitions are missing.

Although research on household plastic packaging waste is available,[8−11] other plastic waste flows, such as automotive, building and construction, and electronics, have received little attention;[12] Nevertheless, these sectors are assumed to generate substantial amounts of plastic waste, which should be accounted for, to fully address the circularity of plastic. Because of the presence of a wide variety of polymers, chemical formulations, material properties, and contaminants in plastic waste and quality criteria for applying recycled plastic into new products,[10,12,14,15] evaluating recycling pathways is complex. From a recycling perspective, three polymers are vital: polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). PE and PP account for about half of the European plastic production, while PET represents only 8%;[5] however, unlike PE and PP, PET's chemical properties allow for regenerating and maintaining of food-grade quality upon recycling.[16−18] Collectively, PET, PE, and PP represent >85% of plastic packaging produced in Europe and between 26 and 67% of plastic produced in other sectors.[19]

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To understand the importance of individual recycling pathways across applications and sectors, plastic flow systems should be addressed in their entirety. Although few analyses exist in the literature (e.g.[11,20−22]), the specific recyclability of individual plastic fractions, cascading recycling pathways, and potential market saturation are yet to be addressed. A dynamic modeling approach is necessary to capture the temporal developments, whereas addressing "resource quality" and recyclability of individual plastic waste flows is essential to evaluate the feasibility of specific recycling pathways, the cascading utilization of plastic materials,[10,15,23] and potential market effects.

The quality and recyclability of plastic are closely linked to the chemical composition and physical/mechanical properties of plastic waste.[10,15,24] Indeed, plastic waste is heterogeneous, and recycling plastic products from waste into the same applications is not always possible.[15] Plastic is recycled into products with matching raw material quality criteria, thereby (i) potentially substituting virgin plastic production across a range of applications and sectors, (ii) not necessarily closing material loops within the original application sector, and (iii) potentially saturating demand for recycled plastic with low material quality requirements over time.[25] For example, when food and nonfood plastic packaging wastes are mixed during recycling, the resulting recycled plastic cannot be used for food packaging applications,[26,27] thus restricting the substitution of virgin plastic to limited sectors. In applications with lower quality requirements, for example, outdoor furniture, the substituted materials may be wood or other secondary materials rather than plastic.[23] In these cases, recycling would not lead to decreasing virgin plastic production or close plastic loops. To date, no study has analyzed plastic material flows at the system level while accounting for resource quality, recycling cascades relative to applications and sectors, and temporal developments of the system.

The aim of this study is to provide a systematic comparison of initiatives to improve plastic recycling in Europe and minimize the need for virgin plastic production over a period of 50 years, focusing specifically on PE, PP, and PET. The study does not offer a mechanistic forecast of future plastic production but rather evaluates potential systemic options for achieving political targets. The specific objectives include the following: (i) based on an adynamic material flow model, evaluate the importance of resource quality, material stocks, recycling pathways, and demand growth rates for PE, PP, and PET; (ii) evaluate potential contributions to recycling targets and closing material loops of nine scenario initiatives related to plastic demand, plastic waste exportation, product design, waste collection, and recycling technology; and (iii) provide recommendations on the relevance of selected regulatory indicators addressing the "circularity" of the European plastic system.

2. METHODS

2.1. Modeling Approach. System modeling followed three steps:

1. A static material flow analysis (MFA) model was established based on existing data for European PET, PE, and PP flows for 2016. The model was reconciled to determine transfer coefficients (TCs), describing the partitioning of mass input to outputs for each process in the system, by dividing the mass output from a process with the mass input;
2. A dynamic MFA model, representing the baseline scenario, was established including data for plastic demand growth rates, cascading recycling pathways, and the TCs derived from Step 1;
3. Scenarios representing potential initiatives for closing plastic loops in Europe were implemented within the dynamic model based on changes in TCs, recycling pathways, and assumptions about recyclability, each representing a dynamic MFA. These were intended to provide useful insights into system behavior rather than represent future forecasts.

The three steps are described in the following sections, and specific details related to the modeling approach are provided in Section S1, Supporting Information.

The geographical scope was Europe (EU27, the UK, Norway, and Switzerland). The temporal scope was 50 years. The static and dynamic MFA models were developed and reconciled in Excel, following the MFA methodology provided by Brunner and Rechberger.[28]

2.2. System Definition. *2.2.1. Static MFA (Step 1).* Figure 1 presents a conceptual drawing of the model. The model setup for year n (white background), corresponding to the static MFA (step 1), presents all processes and their interrelationships in the system. Manufacturing was categorized into the application sectors as follows: Packaging, Agriculture, Automotive, Building and construction, Electrical and electronics, Fibers, and Others. The packaging sector was further subdivided into Food and Nonfood because of the more restrictive legal requirements for plastic in food packaging[10,29] (Table S1.1).

Within each sector, three product groups were defined as follows: (i) bottles or pipes, (ii) soft two-dimensional products (e.g., foils), and (iii) other rigid products, reflecting differences in manufacturing and material properties important for recycling.[15] For the Others sector, an additional product group, "furniture", was defined to represent outdoor furniture, often acting as a sink for low-quality recycled plastic.[23] Finally, fibers were added to the Fiber sector. For PE, bottles/pipes and other rigid products were considered predominantly HDPE, whereas soft products were predominantly LDPE/LLDPE. An exhaustive list of all flows is provided in Table S1.1.

European production and trade quantities, as well as collection, sorting, and reprocessing efficiencies, representing 2016 conditions, were used to define TCs for all processes in the static MFA. As this study's scope was to assess plastic circularity solely within Europe, all exports were considered losses. To consider the release of PET, PE, and PP waste from the current in-use stock, production of plastic predating the modeling period (1991−2015) was estimated[30] (details in Section S2.4). The amounts of plastic accumulated as the in-use stock in 2016 (n = 1) were estimated using normally distributed lifetime functions (see Table S2.4) applied to plastic products consumed between 1991 and 2016.

To account for the reduced quality of recycled plastic, and thereby reduced applicability, compared to virgin plastic, cascading pathways were defined for each flow. Cascading pathways describe a plastic flow's pathway from waste into a recycled material, that is, into which sector(s) and product group(s) a specific plastic flow is suitable to be recycled. If a

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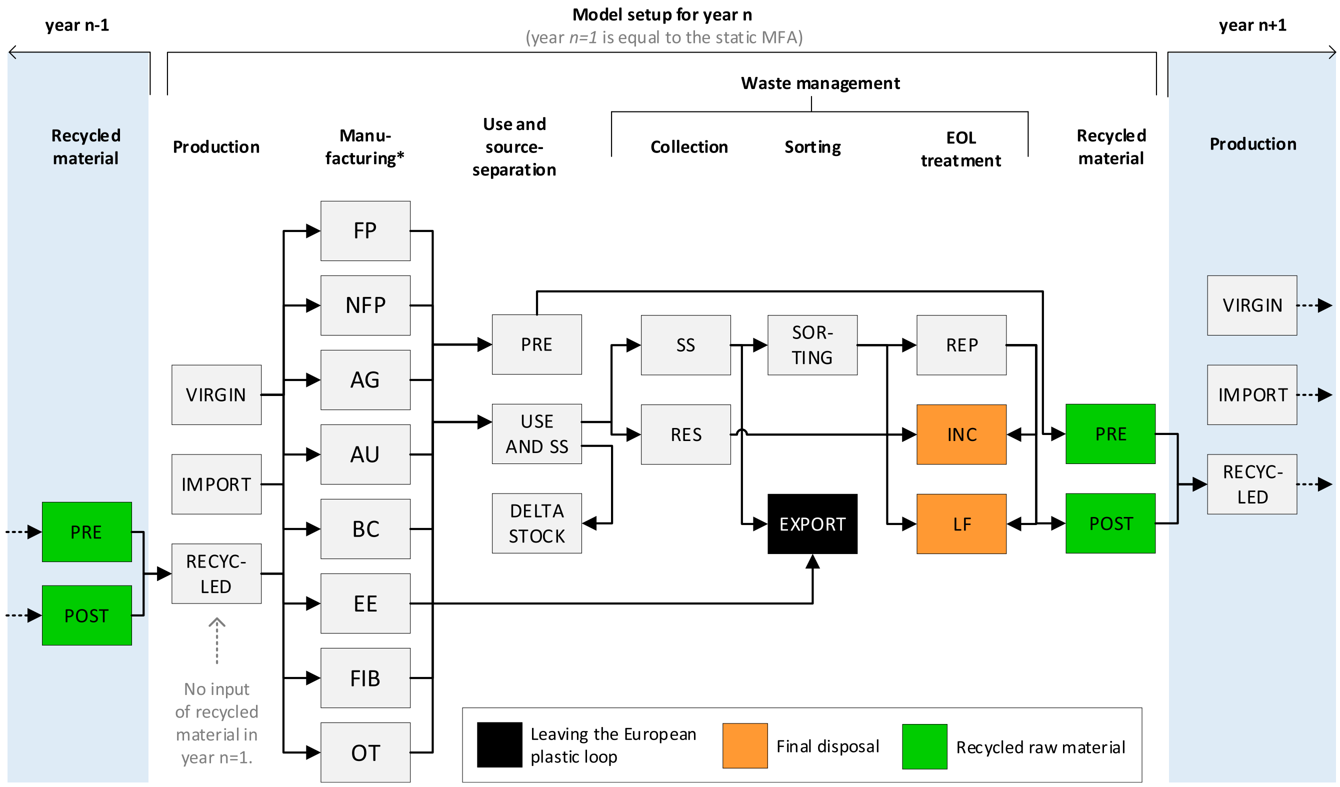

Figure 1. Conceptual drawing of the model and how flows from different years are related. AG: agriculture, AU: automotive, BC: building and construction, EE: electrical and electronics, FIB: fibers, FP: food packaging, INC: incineration, LF: landfill, NFP: non-food packaging, OT: others, POST: postconsumer, PRE: preconsumer, REP: reprocessing, RES: residual waste, and SS: source-separated waste. * For each sector, a limit for the maximum content of recycled materials, RC^{max}, was applied (Table S2.14).

plastic flow of a specific product group from a specific sector is recycled into the same product group and sector, the cascading pathway reflects closed-loop recycling. In contrast, if a plastic flow from a specific sector is recycled into another sector and/or product group with lower or similar quality criteria, the cascading pathway reflects downcycling. "Furniture" and "other rigid products" within the Others sector were assumed to act as a sink for low-quality recycled plastic[23] and, thus, no products from this sector were assumed recycled in order to limit the number of times that low-quality plastic flows was recirculated. Specific cascading pathways are described in Section S2.5.1.

2.2.2. Dynamic MFA (Step 2). The dynamic MFA model was developed for a period of 50 years to ensure that the model was able to sufficiently capture the effects of changes to all flows and sectors in the system. The temporal scope was chosen to appropriately model the effects of initiatives related to production and manufacturing, even for the flows of plastic products with the longest lifetime, that is, Building and construction sector for which 98% of plastic consumed at year $n = 1$ was released as waste within 50 years.

TCs derived from year $n = 1$ (step 1) were assumed constant over time. For simplicity, all material inputs in year $n = 1$ (2016) were assumed to originate from virgin plastic (considered a reasonable assumption, as the share of recycled plastic in Europe was only 6%[4]). However, the plastic accumulated in the in-use stocks at the beginning of the modeling period was also considered in the dynamic model (see Section S2.4).

As illustrated in Figure 1, the recycled materials produced in a specific year (n) [R_n] represented part of the inputs to plastic production in the following year (n + 1). The virgin material consumption [VMC] in year n + 1 was calculated as

$$VMC_{n+1} = C_{n+1} - R_n$$

C_{n+1} is the expected consumption in year n + 1, calculated by applying annual growth rates to the plastic demand from 2016 for each sector's product groups. As the functionality of recycled plastic is often reduced because of the shortening of polymers, mixing of polymers, impurities, etc.,[14,15] the maximum content of recycled plastic was defined for each product group and sector (RC^{max}). This definition ensures that the required functionality within the specific product group and sector is not compromised (see values in Section S2.5.2). Consequently, in most sectors, full substitutability of virgin plastic was not possible and hence

$$R_n \le C_{n+1} \cdot RC^{max}$$

All scenarios were also calculated with $RC^{max} = 1$ (100% substitution possible) to test the sensitivity of RC^{max}. In situations where $R_n > C_{n+1} \cdot RC^{max}$, that is, saturation of markets for recycled plastic, the "surplus" recycled plastic was assumed either further downcycled into the Others sector or, when that sector becomes saturated, lost (incineration and landfill), thereby neither substituting virgin plastic nor contributing to the RR. Although this is an approximation, the actual effects on virgin plastic demand, the market conditions of downcycling, and the availability of surplus recycled plastic are poorly understood. As such, the assumption is considered reasonable.

2.3. Scenario Definition (Step 3). From the dynamic MFA of the baseline scenario (*S0: Baseline*), based predominantly on empirical data for 2016, six prospective

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Table 1. Scenario Overview. Scenarios 1−5 are presented according to how they differ from *S0: Baseline*. EOL: End of life, Specific assumptions and data values are presented in Section S4.

scenario	plastic demand	TCs in EOL	quality aspects
S0: baseline	increasing by fixed rates	same as 2016	cascading pathways as in 2016
Change of Framework Conditions			
S1a: constant demand	zero growth rate, demand maintained at 2016 level	as baseline	as baseline
S1b: No export of waste	as baseline	all the collected plastic waste is managed in Europe	as baseline
Design for Recycling			
S2a: monopolymer design	as baseline	increased recovery and reprocessing	as baseline
S2b: alignment of rigid packaging	all rigid food packaging is PET. All rigid nonfood packaging is PE or PP.	as baseline	all rigid PET is recycled in a closed loop.
Improvement of Collection			
S3: increased collection	as baseline	increased collection. Reduced recovery and reprocessing	products from the others sector is recycled to “other rigids” in others
Technology Improvement			
S4: state-of-the-art EOL technology	as baseline	increased recovery and reprocessing	as in baseline
Combined Scenarios			
S5a: all initiatives, increasing demand	all rigid food packaging is PET. All rigid nonfood packaging is PE or PP.	increased collection, recovery, and reprocessing. No waste exports.	rigid PET food packaging is recycled into food packaging.
S5b: all initiatives, constant demand	constant demand. All rigid food packaging is PET. All rigid nonfood packaging is PE or PP.	increased collection, recovery, and reprocessing. No waste exports.	rigid PET food packaging is recycled into food packaging.

scenarios representing individual initiatives to increase circularity and/or recyclability of plastic in Europe were defined. Additionally, two scenarios combining several initiatives were assessed to illustrate the potential for full implementation. An overview is provided in Table 1, with further scenario details in Sections 2.3.1−2.3.6, where the description of S1−S5 only focuses on changes from *S0: Baseline* and thus aspects not presented remain identical to the baseline.

2.3.1. Baseline (S0). Scenario *S0: Baseline* involves production data, product lifetimes, waste management and recycling pathways, and annual growth rates corresponding to the European conditions in 2016. All input data are provided in the Supporting Information, including production quantities (Section S2.1), annual growth rates (S2.2), lifetime functions (S2.3), estimation of production before the modeling period (S2.4), modeling of cascading pathways (S2.5.1), RC^{max} (S2.5.2), and all TCs (S2.6). Moreover, a data quality assessment is provided in S3.

2.3.2. Change in Framework Conditions (S1a, S1b). To illustrate a hypothetical steady-state situation where the amount of plastic waste generated in a given year equals the demand, *S1a: Constant demand* assumes that the European plastic demand is constant at a level corresponding to 2016.

S1b: No export of waste represents a situation in which all the plastic waste is managed within Europe, not allowing the exportation of poor-quality plastic waste.

2.3.3. Design for Recycling (S2a, S2b). Design choices may affect the recyclability of products and packaging.[14,31] The “design for recycling” scenarios represent design improvements enabling increased recycling of plastic. *S2a: monopolymer design* assesses changes from complex (i.e., multiple polymers in a product) to simpler design solutions (i.e., single polymer), leading to higher sorting and reprocessing efficiencies.[31] *S2b: Alignment of rigid packaging* was defined to assess the effect of uniform regulation across polymers and collection schemes. The scenario assumes that rigid food and nonfood packaging are distinctively made of PET and PE/PP, respectively. Enforcing a separate collection of rigid plastic packaging allows recycling of all rigid food packaging (only PET) into new food packaging applications,[31] only using current polymer separation technologies.

2.3.4. Improvement of Collection (S3). Inadequate collection of recyclable plastic is a barrier to increasing recycling[11,32] and improvements in collection and source separation are an integral part of the European circular economy strategy.[6] *S3: Increased collection* represents a situation where separate collection systems and higher collection efficiencies are implemented across all sectors (based on Haupt et al.[33]). However, as higher collection efficiencies might lead to higher shares of impurities[33] and plastic products not suitable for recycling, sorting and reprocessing efficiencies were assumed reduced accordingly.

2.3.5. Technology Improvement (S4). Plastic sorting and reprocessing technologies play a key role in recycling and is expected to develop in the future.[4,13] *S4: State-of-the-art EOL technology* represents a situation where sorting and reprocessing efficiencies are at the highest possible levels reported in the literature. S4 represents a mixture of quantity and quality improving technologies, such as the state-of-the-art NIR sorters, ability to recover black plastic effectively, implementation of synthetic fiber-to-fiber recycling technologies, use of additives minimizing the effect of polymer shortening,[17] etc. Consequently, low-quality products from the Others sector are assumed recycled.

2.3.6. Combined Scenarios (S5a, S5b). S5a and S5b combine individual initiatives included in S1b−S4 to evaluate the theoretical potential for achieving a circular plastic economy in Europe. *S5a: All initiatives, increasing demand* illustrates increasing demand similar to the baseline, while *S5b: All initiatives, constant demand* represents a situation where the demand remained constant, as in 2016.

2.4. Evaluation Indicators. Four indicators were applied for evaluating plastic circularity in Europe (Table 2). The recycling rate (*RR*) is an official EU indicator,[34] which here expresses the percentage of plastic waste effectively recycled

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Table 2. Overview of Evaluation Indicators Used for Interpreting the Results

indicator	unit	formula
RR[b]	%	$RR_n = \frac{R_n}{W_n^{\mathrm{tot}}} \cdot 100\%$
CMUR[c]	%	$CMUR_n = \frac{R_{n-1}}{C_n} \cdot 100\%$
CLCR[d]	%	$CLCR_n = \frac{R_n^{\mathrm{same}}}{C_n} \cdot 100\%$
VMC	Mt	$VMC_n = C_n - R_{n-1}^{\mathrm{rec}}$

[a]*R*: total quantity of plastic effectively recycled in year n or $n - 1$ (surplus quantities at market saturation are not included—see Section 2.2.2. Exports, potentially recycled outside of the EU, were also excluded), R_n^{same}: total quantity of recycled plastic entering production of the same product type in the same sector, as it originally was, in year n, C_n^{tot}: total consumption of plastic in Europe in year n, W_n^{tot}: total quantity of waste generated in year n, including waste that is later exported. All are given pr. mass basis [Mt]. [b]Official EU indicator.[34] [c]Official EU indicator.[35] [d]Elaboration of circularity potential.[10]

and used for product manufacturing, thus at the point after reprocessing and upgrading. The circular material use rate (*CMUR*) is also an official EU indicator,[35] expressing the percentage of total plastic demand covered by recycled plastic. It evaluates all recycling equally, only considering the possible downcycling and loss of material quality when this leads to market saturation. Conversely, the closed-loop circularity rate (*CLCR*) expresses the percentage of plastic demand covered by recycled plastic from the same sector and product group. It is a modified version of the circularity potential developed by Eriksen et al.,[10] illustrating the system's ability to close material loops while also maintaining material quality. Finally, the *VMC* indicator expresses absolute quantities (Mt) of virgin plastic needed to fulfill the total annual demand (on top of the recycled content) - quantities that circular economy solutions ultimately aim to minimize.

3. RESULTS AND DISCUSSION

3.1. Baseline Scenario (S0). Figure 2 presents PET, PE, and PP flows in Europe in years $n = 1$ (2016) and $n = 50$ for *S0: Baseline*. The consumption of PET, PE, and PP increased by around 400% over the 50-year period. This increase is in line with projections for the total European plastic demand by the European Commission,[4] predicting the demand to double within 20 years, and Ellen MacArthur[13] predicting a 360% increase from 2014 to 2050. Growth is expected in all sectors but especially pronounced within the Automotive, Packaging, and Fiber sectors (Table S2.3).

In year $n = 1$ (2016), 28 Mt PET, PE, and PP waste was generated. Five Mt was released from the stock whereas the remaining waste were produced the same year, including 14.2 Mt packaging waste (see Table S6.1 for details on stocks). Eurostat reported the generation of 16.3 Mt plastic packaging waste in 2016,[36] of which 14.3 Mt was expected to be PET, PE, and PP.[37] With a difference of less than 1%, this shows the

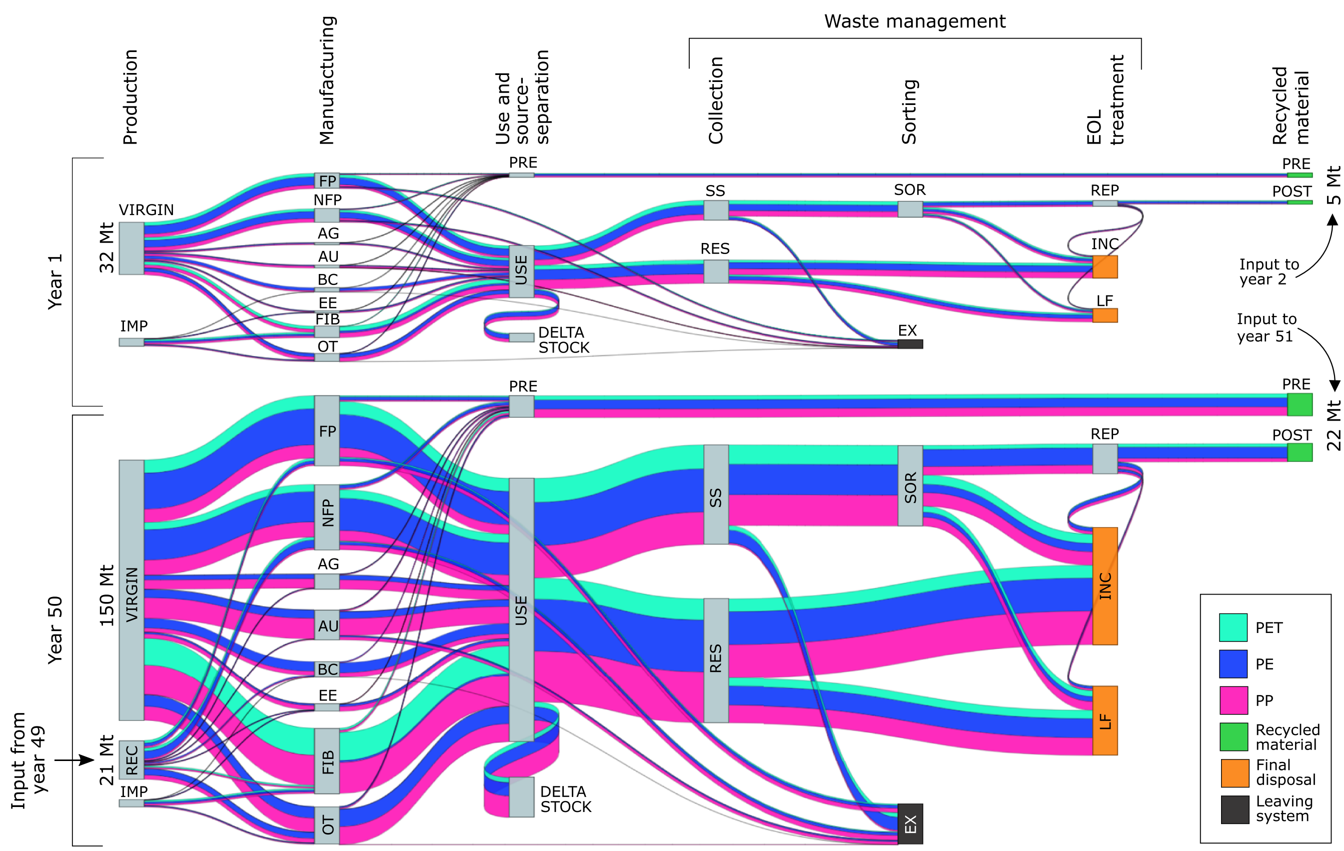

Figure 2. PET, PE, and PP flows in Europe for *S0: Baseline* in years $n = 1$ and $n = 50$. AG: agriculture, AU: automotive, BC: building and construction, EE: electrical and electronics, EX: exports, FIB: fibers, FP: food packaging, IMP: import, INC: incineration, LF: landfill, NFP: nonfood packaging, OT: others, POST: postconsumer, PRE: preconsumer, REC: recycled plastic, REP: reprocessing, RES: residual waste, SOR: sorting, and SS: source-separated waste.

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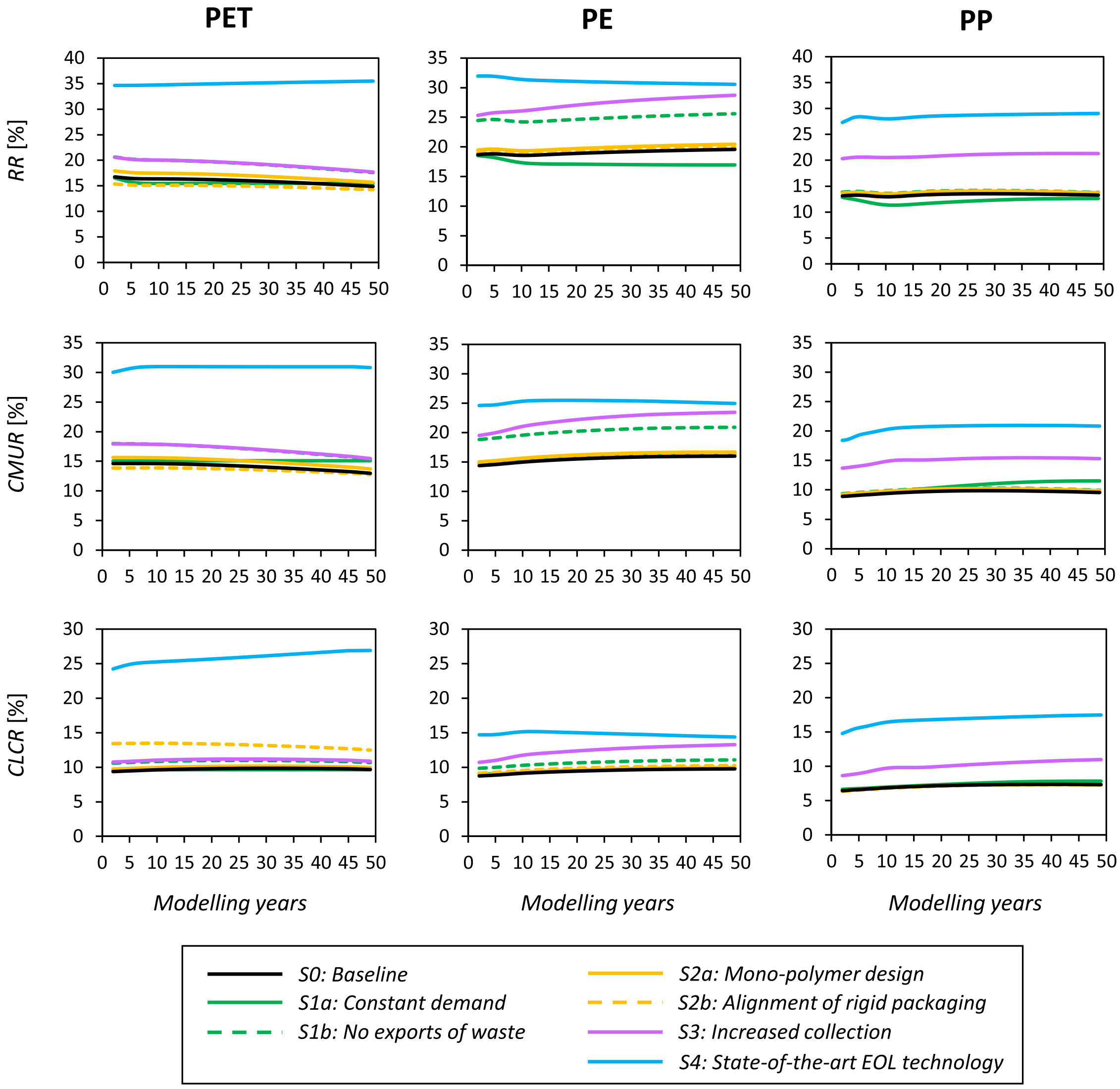

Figure 3. Recycling rate (*RR*), circular material use rate (*CMUR*) and closed-loop circularity rate (*CLCR*) for S0−S4, from year $n = 2$ to year $n = 50$. EOL: End of life.

validity of the model results and good agreement with official statistics. Moreover, only 50% of the generated packaging waste was recycled in year $n = 1$, highlighting a substantial loss of plastic waste, due to ineffective (e.g. packaging) or nonexisting (e.g., automotive) source separation, otherwise available for recycling. Thus, the total collection rate was 50%, corresponding to the *RR* reported in official statistics, 42.4% in 2016,[38] which is noticeably lower. PET, PE, and PP packagings are the plastic types recycled to the greatest extent. Thus, assuming that packaging of other types was not recycled in 2016, the model would provide an *RR* of 42.1% for all plastics, again showing good agreement with officially reported data.

In both years ($n = 1$ and $n = 50$), the quantities of plastic effectively recycled and used in new products (green outputs, Figure 1) are significantly smaller than the losses sent for incineration or landfill (orange outputs), representing 73 and 77% of the generated postconsumer waste in years $n = 1$ and $n = 50$, respectively. These levels correspond well with the 73% loss rate estimated for Austrian plastic packaging waste.[11] In addition to significant losses during source separation, more than 50% of the source-separated plastic is lost during sorting, which is especially evident for PP waste, where almost 70% of the collected plastic is not recovered during sorting (based on Eygen et al.[11]).

Because of the considerable material losses during collection and sorting, less than half of the recycled plastic originates from postconsumer waste and only 5% is suitable for use in the food packaging sector. Thus, postconsumer plastic waste recycling remains far from reaching its full potential, both from a quantity and quality perspective.

Regarding demand, only 12.6% is based on recycled plastic in years $n = 2$ and $n = 50$, corresponding well with the official European *CMUR* of 11.9% for 2016.[39] Besides the considerable losses during recycling, this is because stocks of PET, PE, and PP still grow over 50 years (Table S6.1) because of the increasing plastic demand. Consequently, the waste generated in year $n = 50$ only represented 82% of the plastic demand in that year. As such, 100% waste recycling would still require a virgin material input to meet the demand, corresponding to the estimations by Fellner et al. (2017),[40] indicating that the generated plastic waste is considerably less than the annual plastic demand.

3.2. Effect of Circularity-Enhancing Initiatives (S1−S4). Figure 3 presents the *RR*, *CMUR*, and *CLCR* for *S0:*

Baseline (black line) and individual scenarios S1−S4 (colored lines) during the modeling period.

Most scenarios lead to improvements compared to *S0: Baseline*, with *S3: Increased collection* and *S4: State-of-the-art EOL technology* representing the largest individual improvements across plastic types and indicators. This is owing to the considerable losses during collection and sorting demonstrated for *S0: Baseline* (Figure 2). As collection systems already exist for most PET, the largest improvements are associated with *S4: State-of-the-art EOL technology*, leading to a *RR*, *CMUR*, and *CLCR* of 35, 30, and 25%, respectively. These high values were due to the assumed availability of fiber-to-fiber recycling technology, allowing recycling of fibers (which are not recycled in *S0: Baseline*) and significant increases in closed-loop recycling, as about half of the PET demand is associated with fibers (Figure 2). For PE and PP, noticeable improvements were also observed for *S3: Increased collection*, leading to an *RR* between 25 and 35% and a *CMUR* between 20 and 30%. Especially for PP, containing a considerable share of non-packaging products, not yet having effective collection systems, *S3* provided significant improvements.

For PET and PE, S1b: No exports of waste also leads to considerable improvements in the *RR* and *CMUR* (Figure 3), as 29% of the collected PET packaging and 38% of the collected PE packaging were exported in *S0: Baseline* (Tables S2.17, S2.29). This highlights the importance of trade for the European circularity performance and, hence, the ability to make decisions within political boundaries. However, as the majority of mixed postconsumer packaging plastic is recycled into other sectors (Fibers and Others), the increase in closed-loop recycling was limited, and the *CLCR* performance did not increase to the same extent. *S2a: Monopolymer design* lead to small improvements in the *RR* and *CMUR* performance for PET and PE.

Some scenarios lead to reduced performance. For *S1a: Constant demand*, the *RR* was reduced slightly for all polymers, which reflects that the packaging sector, with high RRs, is assumed to grow faster than most other sectors in the baseline scenario. Hence, the contribution from packaging waste to the overall *RR* is higher in *S0: Baseline* than in *S1a: Constant demand*. However, both *CMUR* and *CLCR* increased slightly over the modeling period for PE and PP.

The effect of *S2b: Alignment of rigid packaging* on PE and PP was negligible. However, for PET, the scenario lead to small decreases in the *RR* and *CMUR*, especially due to increased production of other rigid packaging, compared to those in *S0: Baseline*, as all the other rigid food packaging originally produced in PP were assumed converted into PET (see Table S4.2). Because other rigid packagings were assumed to have significantly lower sorting efficiencies than bottles,[11] this leads to a decreased share of recycled PET, reducing the *RR* and *CMUR*. As opposed, the *CLCR* increased, as all the rigid food packaging was recycled in a closed loop. Data on sorting efficiencies, which were crucial for the performance, were based on Austrian plastic waste and might not fully represent the European situation. Thus, the effect of regulatory alignment of product types across polymers is sensitive to the input data. This highlights the need for better data, such as collection, sorting, and reprocessing efficiencies, not only at the polymer level but also according to product types, on a European scale.

In general, the individual scenarios lead to a maximum *RR* of 35%, which is insufficient to comply with the existing European recycling targets. For most scenarios, the *CLCR* only improved slightly, leading to absolute performances around 10−20%. Moreover, even the best-performing initiative alone could not achieve a *CMUR* above 30%, that is, at best 30% of the plastic demand could be covered by recycled plastic after 50 years.

3.3. Potential for a European Circular Plastic Economy (S5a + b).

The effects of combining initiatives were assessed in *S5a: All initiatives, increasing demand* and *S5b: All initiatives, constant demand* (Figure 4). Both scenarios could potentially reach significantly higher circularity compared to S1−S4 and especially compared to *S0: Baseline*: the *CMUR* increased to around 65% for PET and 45−60% for PE and PP, with only a slightly lower *CLCR* around 60% for PET and 30−45% for PE and PP, reflecting a high increase in closed-loop recycling. Furthermore, the *RR* achieved levels of 50−60% for PP and PE, while 70% for PET. Hence, a combination of several initiatives can improve plastic circularity to a point where primary resources supply only 20−30% of plastic demand and 75−90% of recycling occurs in closed loops.

The highest RRs were obtained assuming an increasing demand, which was because of increasing packaging markets, as explained in Section 3.2. However, the considerable reduction in the *RR* for *S5b: All initiatives, constant demand* for PP was due to the saturation of markets. For PE and PP, several markets got saturated, most of them because of low RC^{max} values. The most important ones for the development of the *RR* were the market for "other rigid products" and "furniture" in the Others sector that became saturated in both scenarios from year n = 2 due to the large quantities of packaging products downcycled into the Others sector. Moreover, for PP, the market for Electronics and Automotive got saturated after 10 years in *S5b: All initiatives, constant demand*, which was not the case for *S5a: All initiatives, increasing demand*. When the market becomes saturated, that is, more recycled plastic is available than the demand required, the surplus material would likely (i) contribute to lowering raw material prices, leading to an expansion of the market for low-quality plastic, (ii) be downcycled to other product groups, or (iii) be landfilled or incinerated. As the Others sector was already assumed to grow more rapidly than the literature suggested (see details in Section S2.2.7) and "other rigid products" and "furniture", acting as a sink for low-quality material, were already saturated, disposal was considered the most realistic option. As a result, a large drop in the *RR* was seen for PP in *S5b: All initiatives, constant demand*, where the market for Electronics and Automotive got saturated. If up to 100% recycled plastic could be absorbed in each sector, this drop would not happen for PP, and the *RR* for both PE scenarios would increase to levels around 55−65% (Figure S7.1). Consequently, significant quantities of the recycled plastic were lost because of the saturation of markets caused by the downcycling and limitation to substitution, both of which are a consequence of reduced quality/functionality. This market shift illustrates that at high RRs, maintaining quality in recycling and minimizing downcycling is important; otherwise, market saturation of low-quality recycled plastics could be critical.

Both *CMUR* and *CLCR* performed considerably better with constant demand, reaching 70 and 65% for PET and 45 and 40% for PE and PP. As for the *RR*, the *CMUR* for PE and PP was limited by the applied RC^{max} values and would increase to levels around 50% if all sectors could absorb 100% recycled plastic without compromising functionality. This projection

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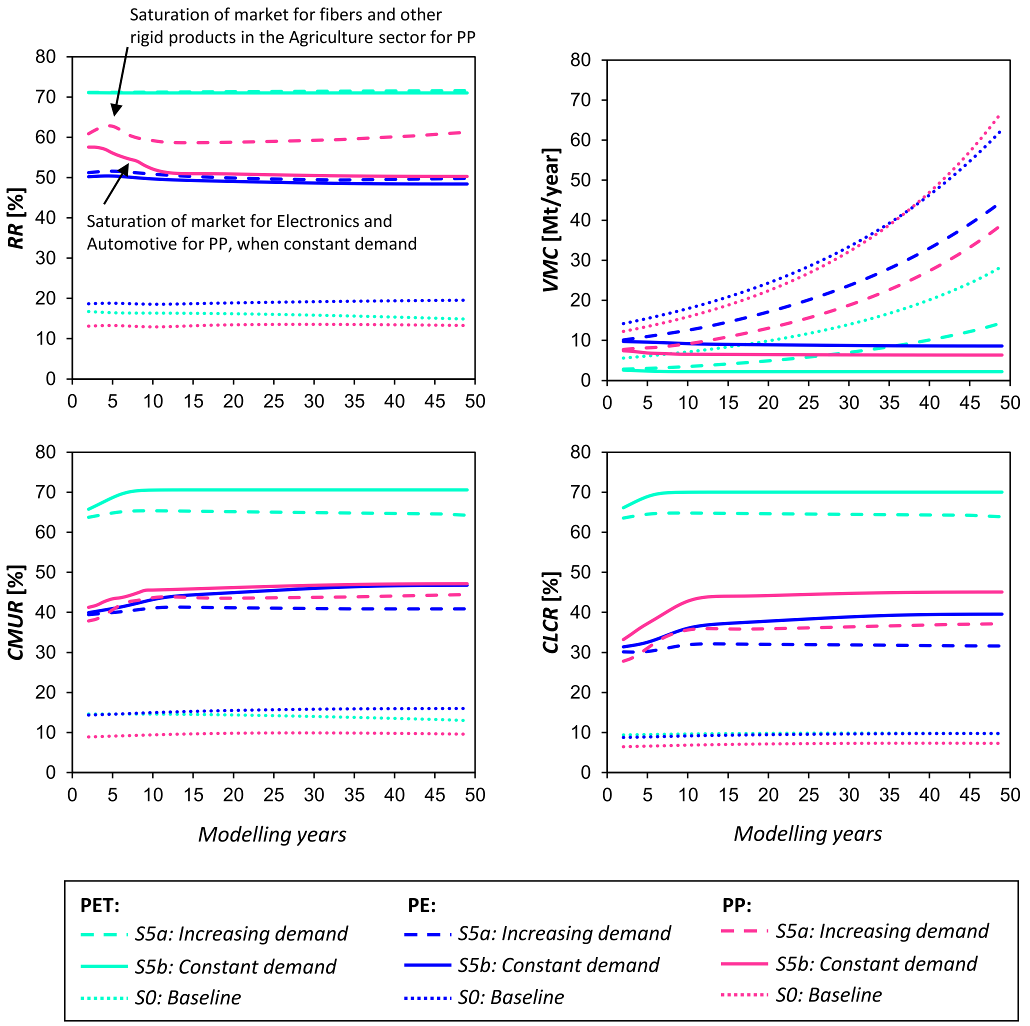

Figure 4. *RR*, *CMUR*, CLRC, and *VMC* [Mt] of PET, PE, and PP for *S5a: All initiatives, increasing demand*, *S5b: All initiatives, constant demand*, and *S0: Baseline*.

further highlights the importance of assumptions related to quality reductions of recycled plastic − an area where more and better data are needed.

The *VMC* supplements the other, more recycling-related indicators, providing the basis for evaluating the absolute dependence on virgin plastic. With constant demand, the *VMC* decreased only slightly over time while increasing dramatically with increasing demand, regardless of the *CMUR* and *CLCR* levels (Figure 4). This development shows that focusing solely on the RRs and even material substitution is insufficient for evaluating the transition toward circularity. In other words, closed material loops and decoupling from *VMC* cannot be achieved by technology improvements alone; the demand must also be stabilized.

3.4. Circularity Evaluation. The *RR* does not reflect issues related to the magnitude of plastic demand—and thereby, how much virgin plastic is needed to support a given system (Figure 4). Thus, the *RR*, which is currently the only indicator converted into mandatory targets for EU member states,[6] is far from sufficient as a measure of plastic circularity. Consequently, the *RR* should be supplemented with targets focusing on plastic demand, preferably while converging on the functionality and quality of recycled materials, such as the *CLCR* and *CMUR*.

The relative indicators are unlikely sufficient to support a transition in society. For example, despite a *CMUR* of 70%, the *VMC* (representing the remaining 30%) is much larger in absolute quantities if the total PET demand increases from 6 to 28 Mt after 50 years, emphasizing the importance of the first step of the waste hierarchy, prevention,[41] also in a circular economy perspective. Thus, if the circular economy's purpose is to minimize dependence on virgin materials, to which large environmental impacts are related,[42] the relative indicators should be supplemented by absolute indicators such as the *VMC*.

3.5. Model Validity and Application. The major flows in *S0: Baseline* in year $n = 1$ (2016) were found comparable to the official statistics for 2016,[38,39] and the total growth over 50 years was within the range of current predictions for plastics.[4,13] The overall trends of the baseline model were considered sufficiently representative of a business-as-usual situation. However, several major sources of uncertainties are related to the model (see Table S3.1 for input data quality): (1) data on how the waste management system handles individual product flows were often scarce and based on data for individual countries rather than Europe, (2) limited data quality for nonpackaging products, and (3) uncertainties related to quantification of the consequences from quality reductions, such as cascading pathways and maximum recycled content—ultimately affecting the potential for market saturation.

Although the modeling results should not be understood as precise predictions of flow quantities when implementing specific technologies or political initiatives, the study provides a first attempt of holistic and system-oriented assessment of the development of the European plastic circularity over time, considering quality reductions. Hence, the results are suited to identify potentials for moving toward a circular plastic economy, related to extensive, system-oriented initiatives, often representing maximum potentials, as closed-loop recycling was assumed for most nonpackaging sectors, where no data were available. Moreover, the results highlight the need for (more detailed) data, pointing toward limitations of current indicators used to evaluate circularity performance.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c03435.

Detailed description of the model, all input data used in the baseline and prospective scenarios, data quality assessment of the input data, and detailed result values (PDF)

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Notes

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