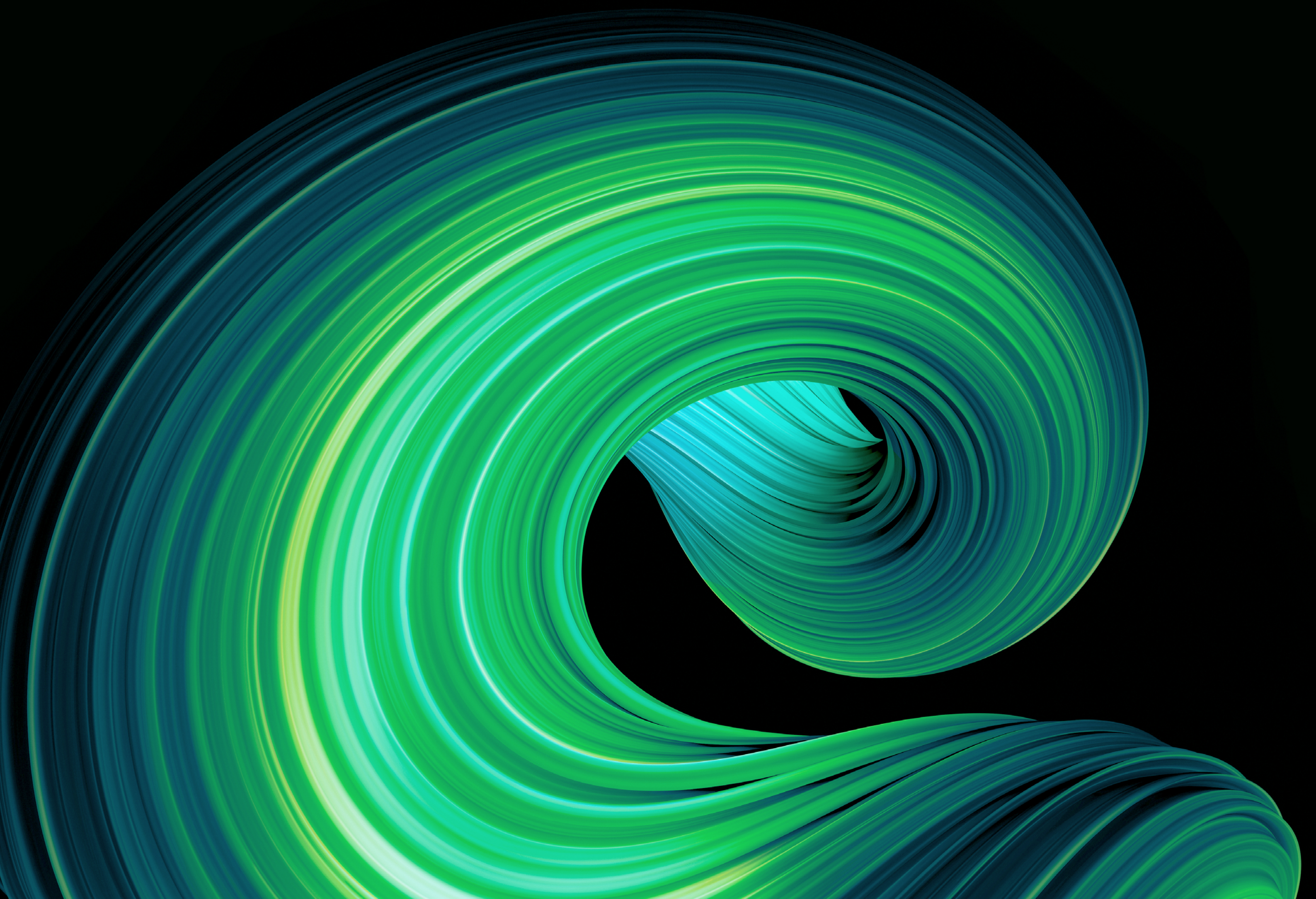
SYSTEMIQ

April 2022

ReShaping Plastics

PATHWAYS TO A CIRCULAR, CLIMATE NEUTRAL PLASTICS SYSTEM IN EUROPE

Technical Appendix



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"ReShaping Plastics" – Method appendix and detailed assumptions

The methodology of "ReShaping Plastics" is largely derived from the "Breaking the Plastic Wave" report published by SYSTEMIQ and The Pew Charitable Trusts as well as the resulting peer-reviewed article 'Evaluating Scenarios Toward Zero Plastic Pollution' published in Science in July 2020. The focus in the report is on unpacking the findings of the model and analysis with a deliberate attempt to minimise explaining the process and assumptions of the analysis. However, below is a more detailed explanation of the approach taken to developing the model, the scenarios and respective key assumptions.

Contents

Introduction

This report explores viable pathways towards a circular, net-zero European plastics economy from 2020 to 2050. The findings of the report are based on the "Reshaping Plastics" model. This Technical Appendix highlights the methodology and approach to the modelling as well as the scenarios and corresponding key assumptions.

The "Reshaping Plastics" model projects volumetric stocks and flows of plastics in four sub-systems in the EU 27 countries plus the United Kingdom for the years 2020-2050. The sub-systems analysed – packaging, household goods, automotive and construction – are explained in the section "Sub-systems and plastic categories". The projections are based on the "Do Nothing" scenario which extrapolates as is data for plastic utility[1], demand and waste from 2020 towards 2050. In this scenario, the model

[1] The concept of plastic utility is integral to the modelling undertaken in this study. As an overarching concept, utility refers to the satisfaction of 'needs received by consuming a goods or a service'. For the purpose of this study, plastic utility is defined as the services provided by plastic under a Do Nothing Scenario, such as protection or food preservation. In alternative scenarios, plastic utility can be provided through other goods and services with less (virgin) plastic use. The demand for plastic utility is derived from the amount of plastic utility minus volumes of plastic reduced or substituted. Plastic demanded turns in waste depending on the lifetime of the plastic application (i.e. how long the plastic remains in-stock).

quantifies different stocks and flows in the system, and the relationship between them, as shown in the system maps in the sections "System maps as basis for model". Based on this, the Current Actions scenario includes the expected effects of legislations in place plus industry commitments. This scenario serves as the baseline results to reflect ongoing developments in the plastic system. Thus, the baseline growth of volumes from 2020-2050 includes several policies and industry commitments that have an effect on absolute plastic utility, demand and waste volumes. To the respective plastic volumes, cost, GHG emissions, and employment numbers are matched to obtain a comprehensive socio-economic and environmental assessment. When analyzing GHG emissions, the scope of the study covers the production and end-of-life carbon emissions only. The use-phase emissions benefits of plastic (e.g., insulation of buildings, light-weighting of vehicles, and more) are not quantified within this study although they are considered in the analysis.

A range of scenarios have been modelled to establish potential pathways towards circularity and GHG reduction. These scenarios are not forecasts, nor are they the only possible scenarios. They are one view among an almost infinite number of scenario variations that can be generated. However, they are intended to represent the most illuminating combination of possible pathways, to help guide plastics system decision-making both within and between stakeholder groups. The scenarios were constructed by identifying systems change levers, for example the elimination of unnecessary plastic, automotive design for disassembly, or the scaling up of chemical recycling, and then quantifying the maximum possible efficacy of these levers (as constrained by key system factors) on the system baseline over the 2022-2050 time series.

A note on uncertainty

These systems change levers aim to establish the most likely impacts of the technologies available to drive change in the plastics system today. The analysis assumes that major change is possible with adequate policy, behaviour change, financing, leadership, and technology. Given the high level of uncertainty inherent in any exercise that takes a 30-year forward-looking view, significant margins of error must be assumed for the outputs, especially in the later years. This uncertainty has multiple drivers: some levers may run into "real-world" barriers that are difficult to predict; the cost of certain technologies (e.g., carbon capture and storage, green hydrogen, and others) may vary significantly; implementation of policies may not happen as expected (e.g., institutional reform in waste collection); international supply chains could mean that Europe cannot rely on product redesign to the extent required; required investments may not come to fruition; and potentially other factors. Despite this uncertainty, comparisons among scenarios can be very informative and help show both the relative impact of different levers and the necessary pace of change.

Modelled scenarios were designed using the best available information to inform mass flows and costs, yet the model does not capture all the components and complexity of the European plastic system. Because gaps exist in data on the generation, collection, recycling, disposal, and leakage of plastic waste, the model is unable to accurately measure all feedbacks in the system. Model design and construction required expert judgment to fill data gaps and estimate current and potential rates of change for the system components, which were then used to generate scenarios. As a result, the analyses include inherent assumptions and are unable to determine system sensitivities to important external drivers, such as the price of oil. In addition, a European model has, by definition, limited granularity, and our conclusions need to be applied carefully to local contexts.

Despite these limitations, the model results are informative as long as they are appropriately contextualized. This means that, rather than providing specific directions for government and industry decision-makers to pursue at individual locations, outputs should be viewed as a system-level assessment of potential futures based on a broad suite of actions and stakeholder priorities. Ultimately, the model and analysis of this report seek to explore the potential to transition to a circular, net-zero plastics economy by analysing constraints and potential for scaling of different interventions, based on historical trends and developments. As such, this report seeks to understand what is possible and what are the measures required to activate the potential towards a circular, net-zero European plastics system.

Sub-systems and plastic category taxonomy

The scope of this study covers 75% (36.9 Mt) of total European plastic demand and 83% of known waste generation, focusing on EU 27+1 countries. The analysis considers the four largest plastic consuming sectors: packaging[2] (34%); non-packaging household goods (11%); the construction sector (21%); and the automotive sector (9%), as shown in Figure A1. These sub-systems are further split into respective plastic categories:

- <u>Packaging (sub-system)</u>: **Beverage bottles** [a food-grade bottle used for water, beverages, and other drinks applications], **Rigid monomaterial** plastics [an item made from a single plastic polymer that holds its shape such as a non-food bottle or tub], **Flexible monomaterial** plastics [an item made from a single plastic polymer, that is thin such as plastic wraps and bags], **Multilayer** plastics [an item, usually packaging, made of multiple plastic polymers that cannot be easily and mechanically separated], and **multimaterials** [an item made of plastic and non-plastic materials - such as thin metal foils or cardboard layers - that cannot be easily and mechanically separated].
- **<u>Household goods (sub-system):</u> Hygiene and sanitary products** [plastic portion in hygiene and sanitary products such as diapers, wet-wipes, and toothbrushes], **Multimaterial** [household goods consisting of multimaterial plastic compositions such as toys and furniture], **Rigid mono-material** [household goods that consist of rigid mono-material (PP)].
- **<u>Automotive (sub-system):</u> Bumpers and fuel tanks** [large automotive parts such as bumpers and fuel tanks consisting of PP or PE polymers], **Other Polyolefins** [other PP/PE components such as cable insulation and interior trims], **Other polymers** [other plastic components based on other polymers than polyolefins (i.e. ABS, SAN, PUR and >30 others). Use cases include car body parts, headlight lenses, instrument panel, seats etc.].
- **<u>Construction (sub-system):</u> PVC** [items made of polyvinyl chloride such as flooring, doors and window profiles], **Polyolefins** [items made from thermoplastics, i.e. a variety of products such as films and sheets that are based on polyolefins (e.g. PP or PE)], **Styrenes** [EPS and PS rigid foam panels used almost exclusively for insulation in walls and roofs, **Other plastics** [other plastics such as PUR, PC, PMMA, PA and others used in smaller quantities and to a much lesser extent].

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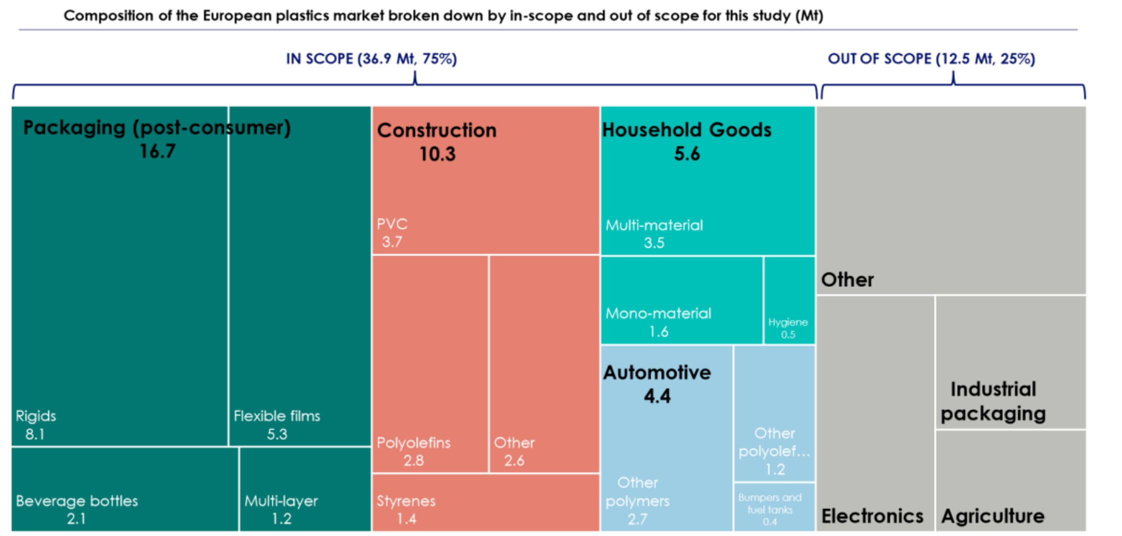
[2] Excluding industrial packaging

The four sub-systems analysed in this study account for 75% (36.9 Mt) of total plastics demand in 2020 in the EU (27+1)



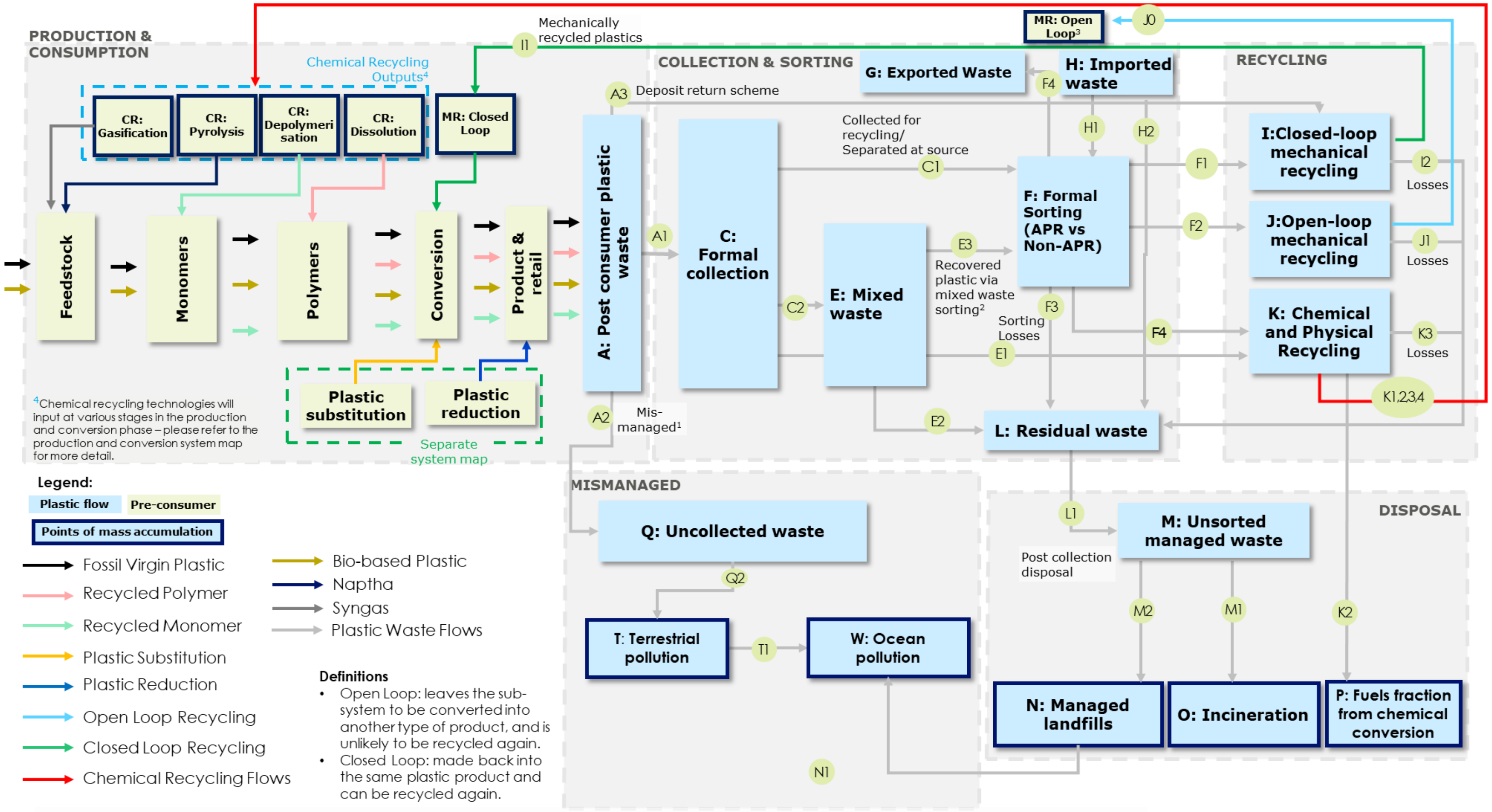
Source: SYSTEMIQ analysis based on WRAP (2018), Conversio (2020), Plastics Europe (2020), Deloitte et al. (2019)

This categorization and assignment of volumes forms the baseline of the analysis. It was developed based on analyses of municipal solid waste composition for packaging and household goods (WRAP[1] and Conversio[2]) and associated volume data by Plastics Europe[3], construction data reported by Plastics Europe[3], vehicle registration statistics from Eurostat[4], and data on the automotive sector from Deloitte et al.[5] All references to plastic in this report refer to these four categories only, unless otherwise explicitly stated. Plastic was grouped into these sub-systems according to its specific behaviour so that flows and levers over time can be modelled. Industrial packaging, agricultural plastics, tyres, microplastics, electronics and fibres are all outside the scope of the study.

System maps as basis for model

The above-mentioned sub-systems are represented by system maps (see Exhibits A2-A4) as a basis for the stock-and-flow model. Plastic was grouped into these sub-systems according to its specific behaviour so that flows and levers over time can be modelled. For each of the boxes and arrows in the system map and for each of the plastic application categories within the respective sub-systems and under different scenarios, plastic volumes and flows were quantified using best available data from literature and expert interviews. Additionally, the following metrics were mapped to the volumes: Cost in EUR per tonne of plastic, GHG emissions in CO2e per tonne of plastic, employment in number of jobs per tonne of plastic.

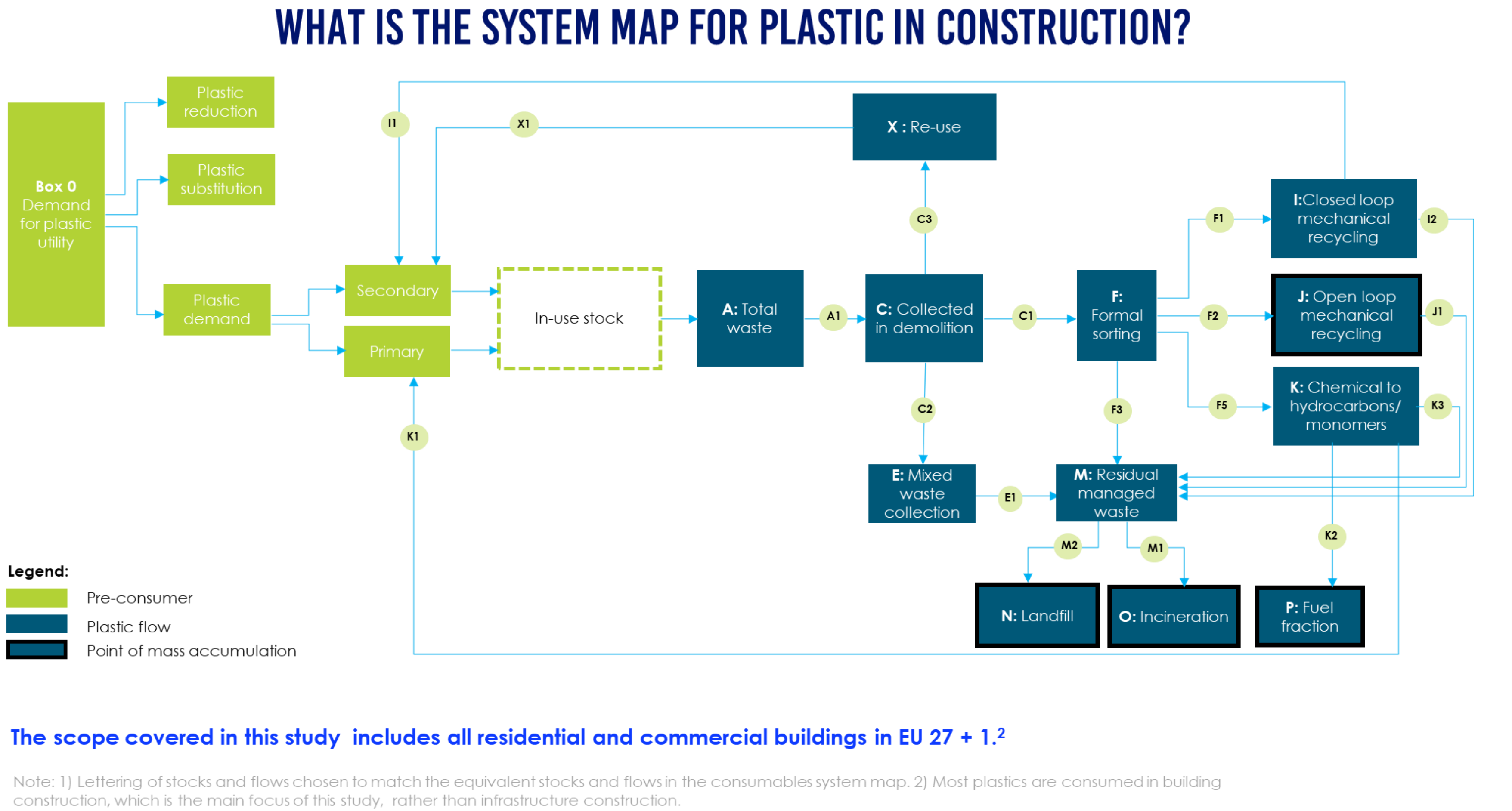
Figure A2: System map for packaging and household goods



¹Mismanaged waste stream include littering, home burning and some dumping/burning. ²Mostly via MBTs. ³Open loop mechanically recycled plastics to other sub-system

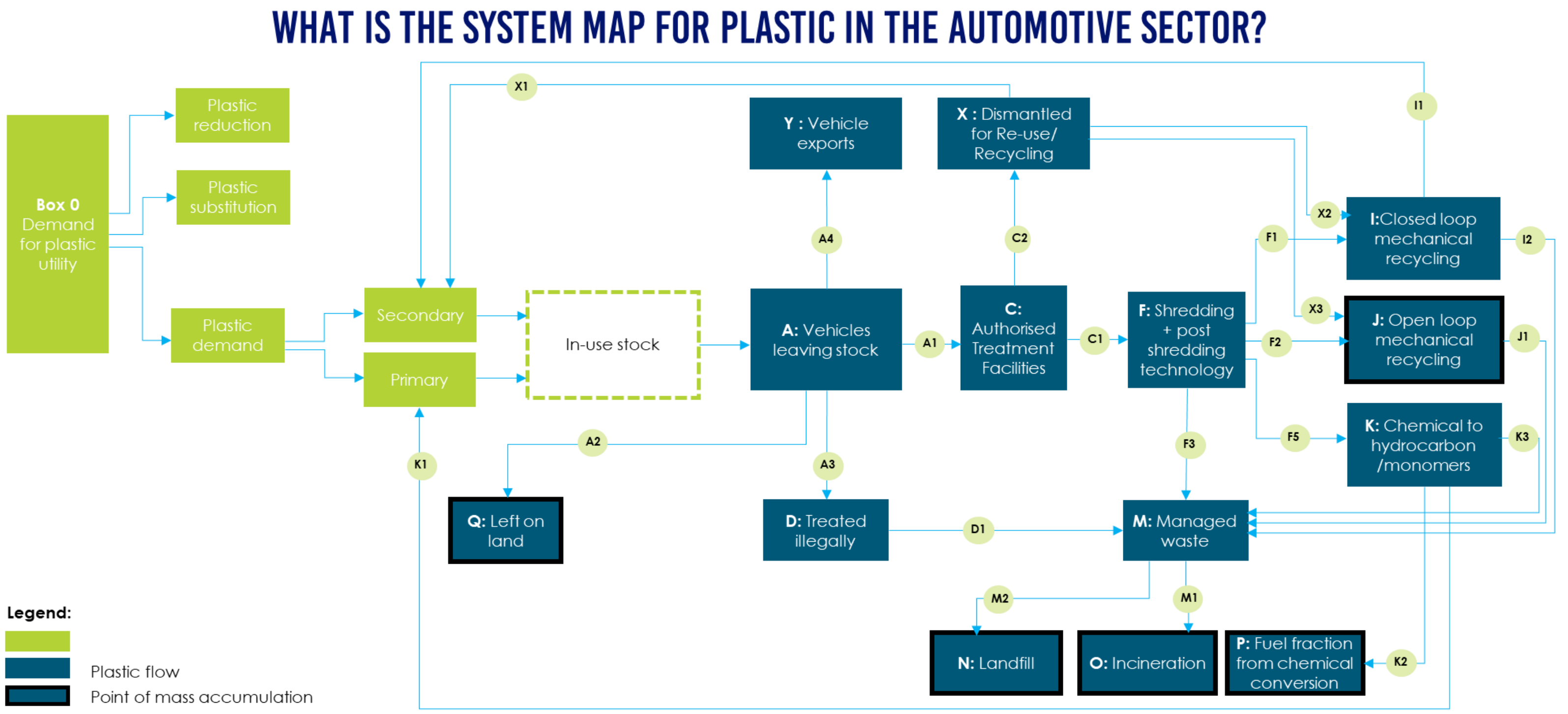
The plastic packaging value chain was categorized into five major components: production and consumption; collection and sorting; recycling; disposal; and mismanaged (depicted with dashed grey outlines). The boxes labelled with letters (A to W) represent mass aggregation points in the model, and the arrows represent mass flows. Boxes outlined in solid lines represent places where plastic volumes leave the system. The boxes to the left of Box A reflect plastic production and demand. Contrary to the global plastic system map introduced in BTPW, everything related to informal collection and post-collection mismanaged waste was excluded as this is deemed irrelevant in an European context.

Figure A3: System map for construction plastics



The same rationale as for packaging applies, but the behaviour of plastics within the construction sub-system deviates. Especially with respect to in-use stock, construction plastics have a significantly higher lifetime than consumables. Also, end-of-life treatment differs significantly with demolition being the point where plastic gets collected.

Figure A4: System map for automotive plastics



The scope covered in this study includes all passenger vehicles, lorries and buses in EU 27 + 1.

Question to experts: How differently do buses and lorries behave at end-of-life compared to passenger vehicles?

Note: Lettering of stocks and flows chosen to match the equivalent stocks and flows in the consumables system map

The same rationale as for packaging applies, but the behaviour of plastics within the automotive sub-system deviates. Especially with respect to in-use stock, automotive plastics have a significantly higher lifetime than consumables. Also, end-of-life treatment differs significantly with shredding in authorised treatment facilities being the point where plastic gets collected for recycling in the form of dismantling and/or auto shredder residue.

Metrics used to quantify systems

	Circularity[1]	GHG emissions (CO_2)	Cost (€€€)	Jobs[2]
Definition	(Total plastic utility − disposal − pollution) / Total plastic utility	Net system emissions (i.e. after carbon capture)	Net system cost (including Opex, Capex and Revenues from recycled materials)	Net direct employment of the system

System definition

Question	Decision	Rationale
What is "Europe"?	EU 27 + 1 (UK)	Data is more readily available across this geography (now and likely for the coming years)
(Production / Use / Disposal) What is considered European plastic?	Used in Europe[1]	Modelling plastics consumed in Europe vs produced or disposed of represents the bulk of the European plastics system, is simpler and the data is more robust
(20X0) What timeline does the analysis cover?	2020-2050	Closer alignment with major European targets and policies re circular economy and climate

Scenario overview

Based on historical values for 2020, the model extrapolates plastic volume flows and associated metrics until 2050. This is done for six scenarios to evaluate the application of different system interventions and system intervention levers (see Figure A5). These interventions and levers have different impacts on the stock and flow model and estimate likely effects of their application under certain conditions.

1. **Do Nothing scenario:** based on plastic volumes identified in the academic and non-academic literature, the Do Nothing scenario extrapolates values for 2020 to 2050 that does neither incorporate policy and industry commitments nor any circularity and GHG reduction levers.
2. **Current Actions scenario:** This scenario incorporates quantifiable policy and industry commitments and serves as the reference scenario for subsequent analyses.
3. **Single lever scenarios** (Reduction & Substitution Scenario and Recycling Scenario): To assess the effects of applying system interventions singularly, the single lever scenarios only include the respective system intervention levers for Reduction & substitution and Recycling.
4. **Circularity scenario:** the circularity scenario incorporates all circularity system interventions and levers to assess pathways of the modelled sub-systems towards increased circularity.
5. **Retrofit System Change scenario (RSCS):** the RSCS scenario builds on the circularity scenario and incorporates GHG reduction levers to existing system infrastructure. It aims to retrofit the existing system infrastructure and operating model with low-emissions fuel and carbon capture.
6. **Net Zero System Change scenario (NZSCS):** the NZSCS adds to the RSCS approach by displacing some fossil feedstock with alternative sources of carbon and employs direct electrification in production to elaborate pathways to net zero.

Scenarios as defined by applying groups of systems change levers							
	Baseline		Individual lever scenarios		Circularity scenario	Systems Change scenarios	
System change lever groups	**Do Nothing** (no action)	**Current Actions** (incl. industry & gov't commitments)	**Recycling** (incl. D4R, collection, Mec Rec, Chem Rec at scale)	**Reduction & Substitution**	**Full Circularity** (Recycling + R&S)	**Retrofit Systems Change Scenario** (retrofitting GHG reduction to the legacy fossil system)	**Net Zero Systems Change Scenario** (breaking free from fossil dependence)
Policy & industry current actions		✓	✓	✓	✓	✓	✓
Recycling levers			✓		✓	✓	✓
Reduction & substitution levers				✓	✓	✓	✓
Innovative GHG reduction levers						✓	✓✓

Do Nothing scenario: Utility, demand, and waste volumetric projection

The Do Nothing Scenario estimates the environmental, economic and social implications of the European plastic system assuming that no major intervention from policy-makers or industry takes place based on historical trends. However, it does account for existing policies and trends such as income growth. The first step in the model is to quantify total plastic utility and demand as well as plastic waste generation and the respective composition for each of the sub-systems and respective plastic categories. The foundation of our analysis is based on these three components:

(1) current and projected plastic utility and demand,

(2) current and projected plastic waste generation, and

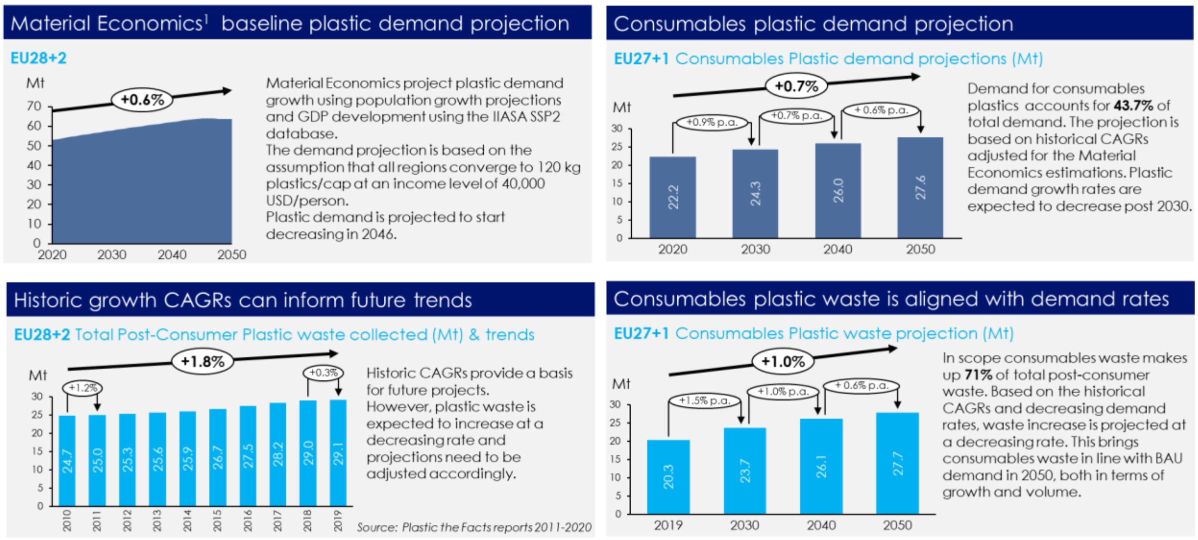
(3) current and projected plastic composition

Subsequently, for each of the boxes and arrows in the system maps and for each of the plastic application categories within the respective sub-systems, plastic flows were quantified using best available data from literature and expert interviews. To the points of mass accumulation, cost in EUR per tonne of plastic, associated GHG emissions in CO2e per tonne of plastic and emission flows, Employment in number of jobs per tonne of plastic were mapped. Thereby, the cost do not include revenues or margins to show the cost to the system. For example, in the plastic production steps, the full capex and opex per tonne of monomer are followed by the gross cost of polymer and converted polymer added to it. These costs are not netted off by revenue along the value chain.

Packaging and household goods (consumables)

The projection for the packaging and household goods sub-systems estimates the environmental, economic and social implications of the European plastic system assuming that no major intervention from policy-makers, industry or investors takes place. However, it does account for existing policies and policies and trends such as income growth, and higher consumption. Growth of plastics demand and waste generation is projected as outlined in Figure A6 based on Material Economics and Plastics Europe.[3,6] The demand composition remains constant up to 2050 and waste composition develops in accordance with past demand composition: waste generation are assumed to be aligned with demand rates in 2050. Additionally, the changes in the composition of this sub-system per plastic category and application is projected using Grand View Research historic and forecast estimates (see Figure A7).[7]

CONSUMABLES DEMAND AND WASTE ARE ALIGNED OVER THE TIME SERIES OF THE MODEL



Note(s): [1]Material Economics. The Circular Economy: A Powerful for Climate Mitigation. 2018.

THE CONSUMABLES PLASTIC CATEGORISATION BREAKS DOWN INTO 5 SUB-CATEGORIES AND 15 PLASTIC APPLICATIONS – PACKAGING 75%, HOUSEHOLD GOODS 25% - WITH MINOR PLASTIC MIX EVOLUTION

The consumables taxonomy is based on UK WRAP data, consistent with German composition using bottom up analysis and Conversio data

Development of Plastic demand per category [1]

	2020	2030	2040	2050
Bottles	2.1Mt (9.4%)	2.2Mt (9.2%)	2.3Mt (9.0%)	2.4Mt (8.8%)
Rigids	8.1Mt (36.3%)	8.6Mt (35.5%)	9.0Mt (34.7%)	9.4Mt (33.9%)
Flexibles	5.3Mt (23.8%)	5.8Mt (24.0%)	6.3Mt (24.3%)	6.8Mt (24.5%)
MLMM*	1.2Mt (5.5%)	1.4Mt (5.8%)	1.6Mt (6.1%)	1.8Mt (6.4%)
HG**	5.6Mt (25.1%)	6.2 Mt (25.5%)	6.7Mt (25.9%)	7.3Mt (26.3%)

Product application	% of total plastic in MSW*** 2020	Packaging	
Water bottles	1.3%	Yes	75%
Other food-grade bottles	8.1%	Yes	
Non-food-grade bottles	5.7%	Yes	
Food service disposables	4.5%	Yes	
Pots tubs and trays	8.2%	Yes	
B2B packaging [rigid mono-material]	3.9%	Yes	
Other rigid mono-material packaging	14.1%	Yes	
Carrier bags	4.1%	Yes	
Films [mono-material]	15.8%	Yes	
B2B flexibles [mono-material]	3.8%	Yes	
Sachets and multilayer flexibles	4.0%	Yes	
Laminated paper and aluminum	1.5%	Yes	
Diapers and hygiene	2.3%		25%
Household goods [multi-material]	7.0%		
Household goods [rigid mono-material]	15.7%		

MLMM = Multi-layer/Multi-material; HG = Household goods; MSW = Municipal solid waste
[1] In line with BPW approach, based on Grand View Research Europe Plastic Packaging Market Estimates and Forecast, 2014 - 2025

Collection, sorting and recycling rates (% of waste generated) stay constant to 2050; as do sorting and recycling loss rates. This implies a substantial expansion of waste management capacity, due to plastic consumption growth. No reduction or substitution of plastic assumed. The assumptions and the respective sources for the Do Nothing 2020 waste flows are presented in the Table A1.

PACKAGING AND HOUSEHOLD GOODS: 2020 WASTE FLOW ASSUMPTIONS

Variable	Model ID	Bottles	Rigids	Flex	MLMM	HG	Comments / Sources
Separate collection (sent to sorting)	C1	**65%**	**42%**	**38%**	**0%**	**3%**	Sources: 1)-8); No separate collection of MLMMand only very low levels of HG based on 7)
Mixed waste collection	C2	**35%**	**58%**	**62%**	**100%**	**97%**	Plug-in, as above
Mixed/Residual Waste Recovered via MBT and sent to Sorting Facility for recycling	E3	**3%**	**3%**	**3%**	**0%**	**0%**	Expert opinion
Share of sorted waste to closed loop recycling	F1	**49%**	**31%**	**34%**	**0%**	**0%**	Share of closed loop: share of end market applications of recycled rigids, flexibles and bottles based on PRE (2020) 7)-9); *Note that no recycling of MLMM & HG is assumed*
Share sorted waste to open loop recycling	F2	**36%**	**45%**	**25%**	**0%**	**0%**	
Sorting losses from separate collection	F3	**15%**	**25%**	**41%**	**100%**	**100%**	Sorting losses from Antonopoulos et al. (2021) 3); no recycling of MLMMand HG
Total exported waste	F4	**0**	**1,487 kt**	**0**	**0**	**0**	European Court of Auditors (2020) 9); CAGR 2010-2017: -1.3%
Total imported waste	H1	**0**	**699 kt**	**0**	**0**	**0**	Imports are assumed to decrease at the same rate as exports, since trade in plastics expected to decline overall
Share of closed loop actually recycled	I1	**81%**	**78%**	**55%**	**0%**	**0%**	Bottles, rigids and flex from Antonopoulos et al. (2021) 3); [flex best practice REC1]
Share of closed loop to losses	I2	**19%**	**22%**	**45%**	**100%**	**100%**	Plug-in
Share of open loop actually recycled	J0	**81%**	**78%**	**55%**	**0%**	**0%**	Bottles, rigids and flex from Antonopoulos et al. (2021) 3); the same recycling yields are assumed as in closed loop
Share of open loop to losses	J1	**19%**	**22%**	**45%**	**100%**	**100%**	Plug-in
Share of managed to Incineration	M1	**68%**	**68%**	**68%**	**68%**	**63%**	Share of incineration in total waste disposal as per Plastics Europe (2020) 10); Decrease in landfilling moving to incineration
Share of managed to Engineered landfills	M2	**32%**	**32%**	**32%**	**32%**	**37%**	Share of landfill in total waste disposal as per Plastics Europe (2020); CAGR of -1.2% for packaging; 1.1% for household goods (post-consumer waste) as per Plastics Europe (2020)

Sources: 1) Eurostat (2021): Packaging waste by waste management operations and waste flow 2009-2018. 2) Plastics Europe (2014-2019): Plastics the Facts; 3) Antonopoulos et al. (2021): Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers; 4) Deloitte (2017): Blueprint for plastics packaging waste: Quality sorting & recycling; 5) PetCore & ICIS (2020): European plastic bottle recycling held back by structural shortage of feedstocks; 6) Walker et al. (2020): Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation; 7) PRE & Eunomia: HDPE & PP Market in Europe - State of Play; 8) PRE (2020): Flexible Films Market in Europe - State of Play; 9) PRE (2020): PET Market in Europe – State of Play; 9) European Court of Auditors (2020): EU action to tackle the issue of plastic waste; 10) Plastics Europe (2020): Plastics the Facts 2020

Construction

This projection estimates the environmental, economic and social implications of the European plastic system assuming that no major intervention from policy-makers, industry or investors takes place. However, it does account for existing policies and trends such as income growth. The growth of building stock is projected according to IEA ETP 2016 forecasts.[8] The demand composition remains constant up to 2050 while the waste composition depends on past demand composition. More information on the approach can be retrieved from Figures A8-A9.

DEMAND PROJECTIONS BASED ON BUILDING STOCK GROWTH FORECASTS AND PLASTIC INTENSITY OF CONSTRUCTION

Baseline demand forecast

- Building stock forecasts for Western Europe from the IEA[1] are used and are adjusted for EU 27 + 1.
- Current building stock is estimated using floor area per capita estimates[2] and population (residential area is 75% of total building stock)[3].
- Floor area demolished annually is estimated using lifetime probability distribution (see next slide).
- New construction each year is the sum of replacements of demolished floor area plus new additions to stock (i.e. change in stock from year to year)
- Average plastic intensity of existing building stock is estimated to be **5.5 kg/m2** based on current waste generation[4] and plastic intensity of new construction is estimated to be **20.5 kg/m2** based on reported demand for plastic from construction.
- Plastic intensity of construction is assumed to remain steady in the baseline scenario.
- Total annual plastic demand is equal to the product of plastic intensity of construction and new construction.

	Source	2020	2030	2040	2050
Building stock (billion m2)	IEA (2016), EC (2011), BPIE (2011)	29.8	31.7	33.6	35.5
Floor area demolished (million m2)	(See next slide) lifetime based on Geyer et al. (2017)	296	327	371	528
Floor area built (m2) = new addition to stock + replacement of floor area demolished	Calculation	487	517	559	716
Plastic intensity of construction (kg/m2)	Calculation	20.5	20.5	20.5	20.5
Plastic demand for construction (Mt) = floor area built x plastic intensity of construction	Calculation	10.0	10.6	11.5	14.7

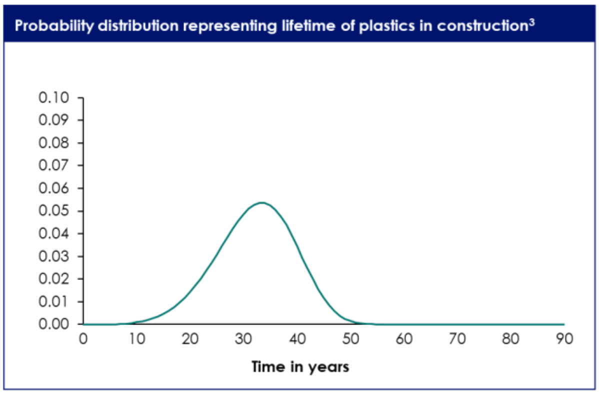
Questions to experts:
- **Do these plastic intensities of new construction and demolition seem realistic? Are these likely to change?**
- **Is there a recommended data source for this?**

Source: 1) IEA (2016), Energy Technology Perspectives 2016 2) European Commission (2011) *Housing space per person 3)* Buildings Performance Institute Europe (2011) *Europe's buildings under the microscope* 4) PlasticsEurope (2018) *The Circular Economy for Plastics*

PLASTIC WASTE GENERATION FROM CONSTRUCTION IS ESTIMATED USING A LIFETIME PROBABILITY DISTRIBUTION WITH AN AVERAGE LIFETIME OF ~35 YEARS

Waste generation forecast

- Construction accounts for the largest waste stream in the EU (374 Mt in 2018)[1].
- Plastic waste makes up only 0.2%-2%[2] of total construction waste. As a result, it is typically not the focus of recovery efforts towards achieving the targets set by the Waste Framework Directive.
- Waste generation today is driven by plastic use ~35 years ago so the use of upstream levers to influence waste in the short term is weak. Downstream levers will be relied on more heavily to tackle this problem in the short term.
- Annual waste from future demand estimated using a lifetime probability distribution with a mean lifetime of ~35 years[3].
- Waste from the existing building stock is estimated to be generated at a constant rate equal to waste generated from construction today.



Source: 1) EUROSTAT Construction and Demolition waste 2) Bio Intelligence Service (2011) *Service Contract on Management of Construction and Demolition Waste – Final Report Task 2* 3) Geyer et al. (2017) *Production, use and fate of all plastics ever made*

Collection, sorting and recycling rates (% of waste generated) stay constant to 2050; as do sorting and recycling loss rates. This implies a substantial expansion of waste management capacity, due to plastic consumption growth. No reduction or substitution of plastic assumed. The assumptions and the respective sources for the Do Nothing 2020 waste flows are presented in the Table A2.

CONSTRUCTION: 2020 WASTE FLOW ASSUMPTIONS

Variable	Model ID	PVC	Polyolefins	Insulation	Other	Source
Separate collection (sent to sorting)	C1	47%	30%	13%	12%	*Calculation based on Conversio (2018) and Antonopoulos et al. (2021)*
Mixed waste collection	C2	53%	70%	87%	88%	*Calculation based on Conversio (2018) and Antonopoulos et al. (2021)*
Collected and re-used	C3	0%	0%	0%	0%	Ginga et al. (2020)
Share of sorted waste to closed loop recycling	F1	44%	20%	0%	9%	Sorted to recycling: Conversio on behalf of PlasticsEurope (2018)
Share sorted waste to open loop recycling	F2	29%	60%	65%	65%	Share of open-loop to closed-loop: Watkins, E et al. (2020)
Sorting losses from separate collection	F3	27%	20%	35%	35%	PlasticsEurope (2018)
Losses from open-loop recycling	J1	20%	22%	34%	30%	Antonopoulos et al. (2021)
Share actually recycled (open-loop)	J0	80%	78%	66%	70%	Antonopoulos et al. (2021)
Losses from closed loop recycling	I2	20%	22%	34%	30%	Antonopoulos et al. (2021)
Share actually recycled (closed-loop)	I1	80%	78%	66%	70%	Antonopoulos et al. (2021)
Share of managed waste to incineration	M1	62%	66%	65%	71%	Conversio on behalf of PlasticsEurope (2018)
Share of managed waste to landfill	M2	38%	34%	35%	29%	Conversio on behalf of PlasticsEurope (2018)

Sources: 1) Ginga et al. (2020) Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production. 2) Conversio on behalf of PlasticsEurope (2018) Plastic waste, recycling, energy recovery and disposal from building & construction in Europe 2018 3) Antonopoulos et al. (2021) Recycling of post-consumer plastic packaging waste in the EU: recovery rates, material flows and barriers 4) Watkins, E et al. (2020) Support to the Circular Plastics Alliance in establishing a work plan to develop guidelines and standards on design-for-recycling of plastic products. Conversio on behalf of PlasticsEurope (2018) Plastic waste, recycling, energy recovery and disposal from building & construction in Europe 2018

Automotive

The projection as highlighted in Figures A10-A11 estimates the environmental, economic and social implications of the European plastic system assuming that no major intervention from policy-makers, industry or investors takes place. However, it does account for existing policies and trends such as income growth, and higher consumption of plastic per vehicle. Growth of vehicle stock and plastic use in vehicles is projected according to historical trends. The demand composition remains constant up to 2050 and waste composition depends on past demand composition.

DEMAND PROJECTIONS BASED ON PER-CAPITA GROWTH TRENDS OF VEHICLES IN THE EU 27+1 AND PLASTIC INTENSITY OF VEHICLE PRODUCTION

Baseline demand forecast

- Vehicle stock forecasts are based on the projected growth in transport demand from vehicles, measured in passenger km, by the T&E's European Transportation Model (EUTRM). The projection assumes that transport demand continues to evolve based on historical trends.
- Number of vehicles leaving stock per year estimated using lifetime probability distribution (see next slide).
- Vehicles entering stock is the sum of replacements of vehicles leaving stock and new additions to stock (i.e. change in stock from year to year).
- The mass of the average passenger vehicle in Europe is around 1.29 tonnes. However, with trends towards light-weighting and stricter emissions standards, the mass is assumed to decrease at a rate of 1% p.a. A similar assumption is made by Becque et al. (2020) in ODI's Phasing out Plastics report.
- Average mass of plastic in a vehicle is estimated to increase by 50% relative to today's levels from ~200kg per vehicle to ~300kg per vehicle.[4]
- Total annual plastic demand is equal to the product of vehicles entering stock, average mass of vehicle and % of plastics by weight.
- Note that the table shows the plastic demand estimated for passenger vehicles only. Buses and lorries are modelled using the same methodology with different parameters. Stocks are projected by assuming constant number of vehicles per capita up to 2050.

	Source	2020	2030	2040	2050
Vehicle stock	Transport and Environment (2018)[1]	290.3	322.8	352.2	381.7
Vehicles leaving stock	(see next slide) lifetime based on Geyer et al. (2017)[2]	14.3	15.6	17.9	20.5
Vehicles entering stock	Calculation	17.2	18.5	20.8	23.4
Mass of average passenger vehicle (kg)	ICCT (2017)[3] – future vehicle mass assumed to decrease by 1% p.a.	1.29	1.16	1.05	0.95
% of plastic by weight	Becque et al. (2020)[4]	15%	20%	25%	30%
Plastic demand (Mt) = vehicles entering stock x avg. mass of plastic in vehicle	Calculation	3.4	4.4	5.5	6.7

Question to experts:

- **Does the -1% CAGR assumption for passenger vehicles make sense? Is there a better way of projecting this?**
- **Does the increase in %of plastic by weight from ~200 kg to ~300 kg by 2050 align with industry projections?**

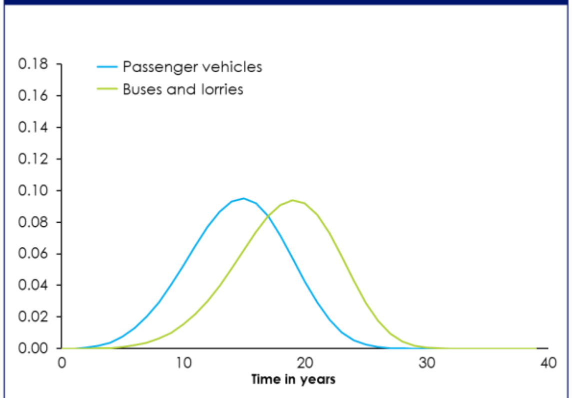
Source: 1) Transport and Environment (2018) *Roadmap to decarbonising European cars* 2) Geyer et al. (2017) *Production, use and fate of all plastics ever made* 3) ICCT (2017) *European Vehicle Market Statistics Pocketbook 2016/17* 4) Becque et al. (2020) *ODI Phasing out Plastics – The Automotive Sector*

PLASTIC WASTE GENERATION FROM THE AUTOMOTIVE SECTOR IS ESTIMATED USING A LIFETIME PROBABILITY DISTRIBUTION WITH AN AVERAGE LIFETIME OF ~13.5 YEARS

Waste generation forecast

- Lifetime probability distribution of vehicles assumed to remain constant over time.
- Number of vehicles leaving stock (including exports of second-hand vehicles) estimated using lifetime probability distribution with a mean lifetime of ~15 years[1].
- For buses, coaches and lorries, the same methodology is used to estimate plastic waste generation but a lifetime probability distribution with a mean lifetime of ~20 years is used instead.
- Plastic waste generated from the automotive sector today is mainly driven by plastic consumption in new vehicles ~13.5 years ago. EUROSTAT data of new registrations of vehicles used to estimate waste generation from past consumption.
- Plastic makes up 10% - 15% of total waste from end of life vehicles and is dispersed throughout the vehicle[2]. As a result, it is typically not the focus of recovery efforts towards achieving the target of the End-of-Life Vehicle Directive.

Probability distribution representing lifetime of vehicles[1]



Source: 1) Ramboll (2020) Plastic Parts from ELVs 2) Trinomics (2020) *Supporting the Evaluation of the Directive 2000/53/EC on end-of-life vehicles*

Formal and informal collection, sorting and recycling rates (% of waste generated) stay constant to 2050; as do sorting and recycling loss rates. Because of plastic consumption growth, this implies a substantial expansion of waste management capacity. No reduction or substitution of plastic assumed. The assumptions and the respective sources for the Do Nothing 2020 waste flows are presented in the Table A1.

AUTOMOTIVE: 2020 WASTE FLOW ASSUMPTIONS

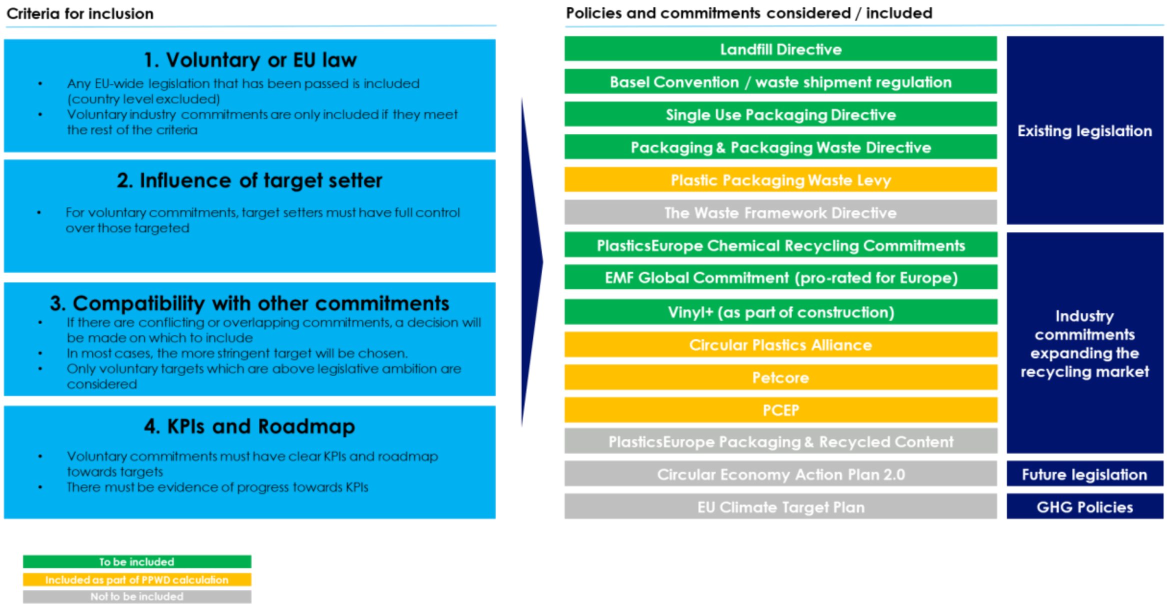
Variable	Model ID	Bumpers and fuel tanks	Other Polyolefins	Flex/multi-material	Source
Sent to Authorised Treatment Facility	A1		59%		Oko Institut (2017)
Left uncollected	A2		3%		Oko Institut (2017) – Specific to Denmark
Treated illegally	A3		17%		Oko Institut (2017) – Specific to Denmark
Exports (incl. illegal exports)	A4		21%		Oko Institut (2017)
Large parts dismantled before shredding (% reused out of total dismantled)	C2	14% (25%)	4% (96%)	2% (98%)	*EUROSTAT, Kawecki et al. (2018), Monier et al. (2019)*
Sent for shredding	C1	86%	96%	98%	*EUROSTAT, Kawecki et al. (2018), Monier et al. (2019)*
Losses from shredding sent to managed waste	F3	68%	76%	91%	*EUROSTAT, Kawecki et al. (2018), Monier et al. (2019)*
Shredded residue sent for closed-loop recycling	F1	3%	2%	1%	WRAP (2019)
Shredded residue sent for open-loop recycling	F2	29%	22%	8%	WRAP (2019)
Losses from open-loop recycling	J1		28%		Deloitte, PRE (2015)
Share actually recycled (open-loop)	J0		72%		Deloitte, PRE (2015)
Losses from closed loop recycling	I2		28%		Deloitte, PRE (2015)
Share actually recycled (closed-loop)	I1		72%		Deloitte, PRE (2015)

Source: 1) Mehlhart et al. (2017) Assessment of the implementation of Directive 2000/53/EU on end-of-life vehicles (the ELV Directive) with emphasis on the end of life vehicles of unknown whereabouts. 2) EUROSTAT (2021) End-of-life vehicles by waste management operations 3) Kawecki et al. (2018) Probabilistic Material Flow Analysis of Seven Commodity Plastics in Europe. 4) Monier et al. (2019) Annual Report the End-of-Life Vehicle observatory – 2017 data 5) WRAP, 2019. Plastics Market Situation Report. 6) Deloitte, PRE (2015) Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment

Current Actions scenario

The Current Actions scenario builds on the Do Nothing scenario and models impacts of government interventions and industry commitments that are expected to materialize in the near future. As such, the Current Actions Scenario serves as the baseline scenario for subsequent scenarios. There are four criteria of inclusion resulting in the Landfill Directive, Basel Convention / waste shipment regulation, Single Use Packaging Directive, Packaging and Packaging Waste Directive, Plastics Europe Chemical Recycling commitment, EMF Global Commitment (pro-rated for Europe) and Vinyl+ being quantified for the respective sub-systems (see Figure A12).

ONLY INDUSTRY AND POLICY COMMITMENTS WITH A HIGH LIKELIHOOD OF MATERIALISING ARE INCLUDED IN THE CURRENT ACTIONS SCENARIO



The Current Actions mainly address packaging and household goods (esp. PPWD, SUPD, EMF GC) as packaging is hitherto the focus sector for plastic regulations. The respective assumptions are highlighted in Table A4 for 2020 to 2050. The policies included reflect quantifiable targets, such as the PPWD target requiring 50% of plastic packaging waste being recycled (sent for recycling) by 2025, and 55% by 2030. To reach these targets, increases in collection for recycling and design for recycling (shift from unrecyclable formats to monomaterials) were modelled.

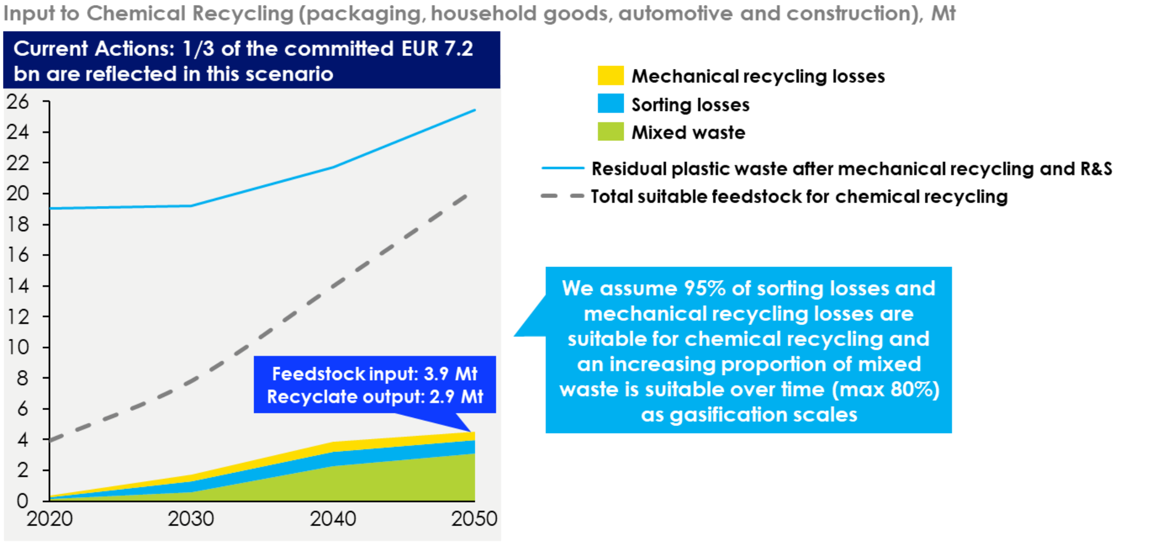
CURRENT ACTIONS PACKAGING & HOUSEHOLD GOODS (2020-2050): SEPARATE COLLECTION AND DESIGN FOR RECYCLING INCREASE, LANDFILLING AND EXPORTS DECREASE

Variable	ID		2020	2030	2040	2050	Comments and source
EMF: Reduce potential	Box 0.1.3	All	0%	1.5%	1.5%	1.5%	SYSTEMIQ analysis based on 1), company commitments made are pro-rated for the European system
SUPD: Reduce potential	Box 0.1.2	Rigid	0%	4%	4%	4%	SYSTEMIQ estimation of the effects of bans and reduction targets under the Single-Use Plastic Directive
SUPD: Reduce potential	Box 0.1.2	Flex	0%	9%	9%	9%	SYSTEMIQ estimation of the effects of bans and reduction targets under the Single-Use Plastic Directive
SUPD: Reduce potential	Box 0.1.2	MLMM	0%	11%	11%	11%	SYSTEMIQ estimation of the effects of bans and reduction targets under the Single-Use Plastic Directive
SUPD: Reduce potential	Box 0.1.2	HG	0%	1%	1%	1%	SYSTEMIQ estimation of the effects of bans and reduction targets under the Single-Use Plastic Directive
PPWD: Shift from Multi to Rigid	Box 0.4.1	MLMM to Rigids	0%	10%	10%	10%	SYSTEMIQ analysis of design for recycling shift of MLMM to rigids required to meet PPWD targets
PPWD: Shift from Multi to Flexible	Box 0.4.2	MLMM to Flex	0%	16%	16%	16%	SYSTEMIQ analysis of design for recycling shift of MLMM to flex required to meet PPWD targets; additional to EMF commitment
EMF: Shift from Multi to Flexible	Box 0.1.4	MLMM to Flex	0%	14%	14%	14%	EMF Global Commitment (based on 1), pro-rated for Europe)
Waste formal collected for recycling (separated at source)	C1	Bottles	65%	90%	90%	90%	SUPD target for 2030; constant afterwards
Waste formal collected for recycling (separated at source)	C1	Rigid	42%	75%	75%	75%	SYSTEMIQ analysis of collection rates required to meet PPWD targets in 2030; constant afterwards
Waste formal collected for recycling (separated at source)	C1	Flex	38%	60%	60%	60%	SYSTEMIQ analysis of collection rates required to meet PPWD targets in 2030; constant afterwards
Total exported waste	F4	Rigid	1,488 kt	705 kt	334 kt	158 kt	-7.2% CAGR, based on export data from 2010-2019, European Court of Auditors (2020) 2)
Total imported waste	H1	Rigid	699 kt	331 kt	157 kt	74kt	-7.2% CAGR, as import reductions assumed under Basel / waste shipment rules

Sources: 1) Ellen MacArthur Foundation (2021): The Global Commitment 2021 Progress Report. 2) European Court of Auditors (2020): EU action to tackle the issue of plastic waste

Additionally, and for all plastic sub-systems, the Plastics Europe commitment to invest EUR 7.2 billion in chemical recycling is reflected in the Current Actions Scenario by quantifying the amount of chemical recyclate produced under certain feedstock constrained and 1/3 of the committed sum (Figure A13). The inclusion of only 1/3 of the sum is to reflect uncertainties attached to the scale-up of chemical recycling technologies. In the Circularity Scenario, the entire amount of EUR 7.2 billion is included. With respect to feedstock constraints, we assume 95% of sorting losses and mechanical recycling losses are suitable for chemical recycling and an increasing proportion of mixed waste is suitable over time (max. 80%) as gasification scales.

GROWTH IN THE CHEMICAL RECYCLING MARKET IS CONSTRAINED BY THE MARKET ADOPTION AND LEVEL OF INVESTMENT



Circularity Scenario

Based on the current Actions Scenario, several systems interventions and corresponding system intervention levers are modelled to estimate the systems impact of increasing circularity. We

For the Circularity Scenario, four high-level system interventions and eight associated system intervention levers have been defined and modelled in the overall analysis (see Figure A14). The system interventions and levers are applied in different scenarios and drive the outcome of the model of the respective plastic sub-system.

FOUR SYSTEM INTERVENTIONS AND CORRESPONDING LEVERS IMPROVE CIRCULARITY IN THE SUB-SYSTEMS WITH VARYING APPLICABILITY

Highly applicable; Partially applicable

System Intervention	System Intervention Levers	Plastics sub-system and applicability of intervention: Packaging	Household	Construction	Automotive	Main responsible stakeholder
#1: Reduction	Reduce plastic through elimination	Highly applicable	Highly applicable			Consumer goods brands; retailers
	Reduce plastic through reuse/ New Delivery Models	Highly applicable	Partially applicable	Partially applicable	Partially applicable	Consumer goods brands; OEMs; construction companies
	Reduce plastic through sharing models for vehicles				Highly applicable	OEMs
#2: Substitution	Substitute plastic with alternative materials	Partially applicable	Partially applicable			Consumer goods brands; retailers
#3: Mechanical recycling	Design for mechanical recycling	Highly applicable		Highly applicable	Partially applicable	Consumer goods brands; OEMs; construction companies
	Expand collection for recycling and sorting	Highly applicable		Highly applicable	Partially applicable	Local governments
	Increase mechanical recycling capacity	Highly applicable		Highly applicable	Highly applicable	Waste management companies
#4: Chemical recycling	Scale up chemical recycling	Highly applicable	Highly applicable	Partially applicable	Highly applicable	Petrochemical industry

System Interventions #1 and #2: Reduction & Substitution

Reducing plastics through upstream innovation can design out plastic waste while retaining the benefits of plastics. This requires rethinking product design and business models. The analysis of this report shows that – with appropriate regulatory support, infrastructure investment, and R&D – it is technically feasible and environmentally beneficial to reduce 25% (9.1 Mt) of projected in-scope plastic demand by 2050 without compromising on functionality. At the same time, 4% of plastics can be substitute with circular materials.

Packaging and Household goods

To estimate the potential to reduce and substitute plastic waste, the municipal solid waste stream and the resulting plastic sub-systems (i.e. packaging and household goods) were divided into 15 plastic application subcategories. For these applications, the applicability of six reduction and substitution alternatives have been assessed to each subcategory based on existing businesses, policies, available technologies, environmental trade-offs, and consumer trends. Each combination of plastic application subcategory and reduce and substitute alternative was scored against five criteria laid out in Figure A15—technology readiness level, performance, environmental footprint, convenience, and cost—with the lowest score determining this combination's "limiting factor" and maximum foreseeable uptake rate over time until 2050.

R&S SOLUTIONS FOR PACKAGING AND HOUSEHOLD GOODS HAVE BEEN INDIVIDUALLY SCORED USING A FIVE-TEST FRAMEWORK TO EVALUATE THEIR MARKET PENETRATIONS

Reduce and Substitute Methodology used for the analysis

a Technology test	b Performance test	c Environmental test	d Affordability test	e Convenience test	Limiting factor			
Does a theoretical reduce (1st pass) or substitute (2nd pass) **intervention exist?**	Does the intervention satisfy **performance & health** requirements?	Does the intervention have a better **environmental footprint** (esp. GHG emissivity)?	Are the **cost implications** of the alternative acceptable?	Is the intervention acceptable for **lifestyle and convenience?**	**Overall score**	**2030 %** of serviceable market reached	**2040 %** of serviceable market reached	**2050 %** of serviceable market reached
Yes: TRL 9, available in multiple locations	Yes: meets the minimum performance requirements for sustained utility	Yes: well managed system can outperform reference application	Yes: net savings to society, or broadly acceptable to consumers	Yes: near or better than BAU	Green	50%	80%	80%
Only at pilot: TRL 5-8	Mostly: does not meet performance requirements for certain applications	Mostly: savings are minimal or on par	Mostly: unacceptable in some consumer segments or products	Mostly: consumers or supply chains would face challenges	Yellow	20%	50%	50%
Only in labs: TRL 1-4	Partially: limited applications only	Partially: small increase of environmental externalities compared to alternative	Partially: eco-conscious consumers only	Partially: eco-conscious consumer only	Orange	1%	10%	20%*
No alternative available	Unacceptable health or performance risk	Unacceptable increase in environmental externalities	Unacceptable cost increase	Unacceptable lifestyle change	Red	0%	0%	0%

*Note: The penetration rate potential in the orange category is capped for the "Elimination" lever at 10% in 2050.

The three Reduce levers Eliminate, Reuse (customer-owned), and New Delivery Models (reuse models operated by commercial organisations) were included in order of priority in terms of costs and environmental impact. First, for each plastic application subcategory, we assessed how much avoidable plastic could be eliminated, through redesign, policy, and consumer incentives. The eliminate lever avoids the need for producing materials in the first place and is assumed to offer 100 per cent cost savings on eliminated plastic without unacceptably reducing utility. Second, we analysed how much of the remaining plastic could be reused by consumers, such as with reusable bags, water bottles, and crockery for sit-in restaurants. Key barriers to this lever are consumer and business convenience, which are not quantified but could be significant if reuse systems are poorly designed or have insufficient policy and financial incentives. Finally, we applied the reuse-new delivery model lever, which is the most effort-intensive of the three levers, as it requires new services and infrastructure to be rolled out and sometimes water resources for washing, but offers the largest reduction potential. This lever is responsible for more than half of all avoided waste under the Reduce and Substitute intervention by 2050 (roughly 60%). It delivers cost savings compared with single-use plastic when new delivery models reach scale, including the cost of purchasing reusable packaging and operating reverse logistics and washing.

For the substitution lever application, the use of any substitute material will involve significant economic costs in both production and end-of-life disposal, as well as environmental impacts and other trade-offs to balance. The Substitute intervention is therefore applied only to the plastic in each of the 15 plastic subcategories that remain after the three Reduce levers have been applied. Substitutions were made only with materials expected to be environmentally beneficial, focusing on substituting nonrecyclable items, monomaterial flexible plastic, and multilayer plastic, which have low recycling rates. The analysis of this system intervention is based on three selected substitution material levers: (a) paper; (b) coated paper with a maximum 5 per cent by weight of plastic coating, which is acceptable to recyclers; and (c) certified and appropriate compostable materials, including compostable plastic and non-plastic materials. The three material substitutes were selected because they are the most prevalent ones available today for replacing problematic plastic films and multilayer flexibles. For paper and coated paper, the rate of substitution uptake was estimated to be higher from 2020-2030 as substitution already takes place. With increasing recyclability of plastic through design for recycling, the environmentally beneficial substitution potential of paper and coated paper is estimated to decrease again.

Table A16 provides an overview of all plastic subcategories in the packaging and household goods sub-system and the result of the 5-test technology selection framework.

OVERVIEW OF PACKAGING AND HOUSEHOLD GOODS APPLICATIONS AND THE RESPECTIVE REDUCE & SUBSTITUTE POTENTIAL AS PER THE SELECTION FRAMEWORK

Product application	Product sub-category	% of product application	Eliminate	Re-use	New Delivery Model	Paper	Coated Paper	Compostables
Water bottles	TOTAL	100%	R	O	G	0	0	R
Other food-grade bottles	Target market for refill (milk, soda, sparkling water)	70%	R	O	G	R	R	R
Other food-grade bottles	Remainder	30%	R	R	O	R	R	R
Non-food-grade bottles	TOTAL	100%	O	R	Y	0	0	R
Food service disposables	Straws, stirrers	1%	Eliminated via SUP Directive Current Commitment					
Food service disposables	On-premise food service disposables	24%	R	G	R	R	R	O
Food service disposables	Off-premise plastic cups	32%	R	Y	G	R	O	R
Food service disposables	Off-premise lids	19%	R	Y	G	O	R	O
Food service disposables	Off-premise containers & clamshells	18%	R	O	G	Y	R	O
Food service disposables	Off-premise cutlery	6%	Eliminated via SUP Directive Current Commitment					
Pots tubs and trays	Fresh fruit/vegetables tray/pot/punnet/tub	28%	Y	O	Y	G	0	0
Pots tubs and trays	Pots/tubs for liquids and creams: Yoghurt, butter, spreads, chocolate/sweets, cream, chilled pot desserts & ice cream pots/tubs	24%	R	0	O	0	O	0
Pots tubs and trays	Meat tray	12%	R	O	0	0	O	0
Pots tubs and trays	Ready meals trays, instant pot snacks	8%	R	0	O	Y	O	0
Pots tubs and trays	Other	28%	R	0	0	0	O	0
B2B packaging [rigid mono-material]	TOTAL	100%	R	0	G	0	0	0
Other rigid mono-material packaging	Remainder	100%	O	0	0	O	0	O
Carrier bags	TOTAL	100%	R	G	0	R	0	Y
Films [mono-material]	TOTAL	100%	O	0	O	O	O	O
B2B films [mono-material]	TOTAL	100%	O	0	Y	0	0	O
Sachets and multilayer flexibles	Sachets	84%	R	0	Y	O	Y	Y
Sachets and multilayer flexibles	Multilayer flexibles	16%	R	0	O	O	Y	O
Laminated paper and aluminium	TOTAL	100%	R	0	O	0	0	O
Household goods [rigid mono-material]	TOTAL	100%	O	0	0	0	0	0
Household goods [multi-material]	TOTAL	100%	O	0	0	0	0	0
Diapers and hygiene (plastic portion)	Sanitary	43%	R	O	0	0	0	R
Diapers and hygiene (plastic portion)	Wetwipes	14%	R	Y	0	G	0	O
Diapers and hygiene (plastic portion)	Cotton bud sticks	1%	Eliminated via SUP Directive Current Commitment					
Diapers and hygiene (plastic portion)	Diapers	43%	R	O	O	0	0	R

Note: 0 indicates that there is no competitive solution available to be tested against the framework.

Further assumptions on plastic mass reduced and plastic content of alternatives are included in the assessment based on case studies, which in sum yields the reduction and substitution potentials as shown in Table A5. These are applied to the baseline stock and flow model and yield the plastic volume reductions as outlined in Section 2b of the report.

	2020	2021	2030	2040	2050
Reduce potential - Eliminate - Bottles - Reduce & Substitute	0%	0%	0%	0%	0%
Reduce potential - Eliminate - Rigid monomaterial - Reduce & Substitute	0%	0%	6%	9%	9%
Reduce potential - Eliminate - Flexible monomaterial - Reduce & Substitute	0%	0%	9%	9%	9%
Reduce potential - Eliminate - Multi-layer / -material - Reduce & Substitute	0%	0%	0%	0%	0%
Reduce potential - Eliminate - Household goods - Reduce & Substitute	0%	0%	1%	9%	9%
Reduce potential - Re-use - Bottles - Reduce & Substitute	0%	0%	1%	6%	12%
Reduce potential - Re-use - Rigid monomaterial - Reduce & Substitute	0%	0%	1%	3%	4%
Reduce potential - Re-use - Flexible monomaterial - Reduce & Substitute	0%	0%	2%	3%	3%
Reduce potential - Re-use - Multi-layer / -material - Reduce & Substitute	0%	0%	0%	0%	0%
Reduce potential - Re-use - Household goods - Reduce & Substitute	0%	0%	0%	1%	2%
Reduce potential - New delivery models - Beverage bottles - Reduce & Substitute	0%	0%	33%	49%	46%
Reduce potential - New delivery models - Rigid monomaterial - Reduce & Substitute	0%	0%	11%	21%	19%
Reduce potential - New delivery models - Flexible monomaterial - Reduce & Substitute	0%	0%	3%	15%	20%
Reduce potential - New delivery models - Multi-layer / -material - Reduce & Substitute	0%	0%	11%	33%	36%
Reduce potential - New delivery models - Household goods - Reduce & Substitute	0%	0%	0%	0%	1%
Substitute potential - Paper - Beverage bottles - Reduce & Substitute	0%	0%	0%	0%	0%
Substitute potential - Paper - Rigid monomaterial - Reduce & Substitute	0%	0%	6%	5%	5%
Substitute potential - Paper - Flexible monomaterial - Reduce & Substitute	0%	0%	2%	1%	0%
Substitute potential - Paper - Multi-layer / -material - Reduce & Substitute	0%	0%	5%	1%	1%
Substitute potential - Paper - Household goods - Reduce & Substitute	0%	0%	0%	0%	0%
Substitute potential - Coated paper - Beverage bottles - Reduce & Substitute	0%	0%	0%	0%	0%
Substitute potential - Coated paper - Rigid monomaterial - Reduce & Substitute	0%	0%	3%	2%	0%
Substitute potential - Coated paper - Flexible monomaterial - Reduce & Substitute	0%	0%	2%	1%	0%
Substitute potential - Coated paper - Multi-layer / -material - Reduce & Substitute	0%	0%	13%	4%	4%
Substitute potential - Coated paper - Household goods - Reduce & Substitute	0%	0%	0%	0%	0%
Substitute potential - Compostables - Beverage bottles - Reduce & Substitute	0%	0%	0%	0%	0%
Substitute potential - Compostables - Rigid monomaterial - Reduce & Substitute	0%	0%	0%	0%	1%
Substitute potential - Compostables - Flexible monomaterial - Reduce & Substitute	0%	0%	2%	6%	10%
Substitute potential - Compostables - Multi-layer / -material - Reduce & Substitute	0%	0%	5%	10%	12%
Substitute potential - Compostables - Household goods - Reduce & Substitute	0%	0%	0%	0%	0%

Construction

In the construction sub-system, only reduction through reuse models have been identified to have an impact based on literature review and expert interviews. Figure A17 highlights the reuse assumptions and its rationale. No economically and environmentally viable substitution has been identified.

REDUCE LEVER IN THE CONSTRUCTION SUB-SYSTEM: EXTENDING THE USEFUL LIFE OF COMPONENTS THROUGH DESIGN FOR DURABILITY ALLOWS MINIMAL REUSE OF COMPONENTS, SPECIFICALLY PROFILES, PIPES AND INSULATION

Driving assumption

- **Re-use restricted by destructive demolition techniques and already very long in-use lifetimes.**
- **Assume very limited reuse potential restricted to small proportion of profiles (~10%), 10% of pipes and 5% of insulation. Reuse relies on modular and standardised design and therefore the maximum reuse potential is not reached by 2050 to due to in-use lifetime lag.**

Supporting factors

- Trend towards modular building design improves recoverability of plastics.
- Modularity and durability typically go hand-in-hand. Modular design reuses and refurbishes ~80% of the components in the envelope of a building that can stand for 100 years or more, avoiding demolition[1].
- The use of material passports would facilitate the recovery of components with potential for reuse.

Limiting factors

- Destructive demolition processes and plastic embedded in the building structure results in damage to plastic components, limiting the reuse potential.
- Waste is often contaminated with paints, fasteners, adhesives and dirt, limiting potential for re-use of individual components.
- Lack of information about the presence of chemicals of concern often resulting in no re-use.

Impact on system stocks and flows

Demand reduction through reuse	2020[2]	2030	2040	2050	Rationale/Assumption
PVC	0%	0%	1%	3%	Max. ~10% of pipes and ~10% of profiles reused
Polyolefins	0%	0%	1%	5%	Max. ~10% of pipes reused
Styrenics	0%	0%	1%	2%	Max. 5% of insulation reused
Other	0%	0%	0%	0%	No reuse potential

Source: 1) Ellen Macarthur Foundation (2015) *Growth Within* 2) Ginga et al. (2020) *Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production*

Automotive

System Intervention #1 and #2: Reduce, reuse, substitute in automotive plastic

Due to tight weight restrictions, the use of plastic in vehicles has already been optimized with no further opportunities for reduction. The potential for the reuse of plastic components is therefore highly dependent on having modular, standardized vehicle designs, using non-destructive dismantling processes, and relies on re-sale channels for used parts, which currently do not exist in a sufficiently large capacity.

For substitution, the cost and weight saving advantages of plastic, compared to alternative materials, means that substitution of plastic is not only unlikely but would be detrimental to the performance of vehicles. In fact, current trends indicate that plastic is likely to continue substituting other materials in vehicle components.

According to the International Resource Panel, sharing models, including both car-sharing and ride-sharing, have the potential to reduce the total European vehicle stock by 13% by 2050. More intensive use of vehicles could decouple car ownership from demand for mobility through, for example, both car-sharing where vehicles are owned collectively but used by individuals through rental, and ride-sharing where vehicles are owned by individuals, but occupancy rates are increased through sharing services. These trends are gaining significant traction and undoubtedly will play a central role in driving the circular economy as the more efficient use of our current vehicle stock, and the materials it is made from, reduces future demand. In turn, according to this study's stock and flow model, this could reduce total plastic demand by 22% and waste by 13% by 2050 relative to the Current Actions Scenario.

System Intervention #3: Mechanical Recycling

The mechanical recycling system intervention consist of three lever groups which differ depending on the sub-system: design for mechanical recycling, expand collection for recycling and sorting, and increase mechanical recycling capacity.

Packaging

Improving mechanical recycling in for plastic packaging is a major cornerstone of current policies and industry actions. To estimate the potentials of a significant uptake in mechanical recycling compared to today, three levers have been modelled:

1. Maximize design for recycling (see note below); See Table A6)
2. Increase collection for recycling (separated at source) and corresponding sorting capacities (i.e. decrease sorting losses); (See Table A6)
3. Enhance mechanical recycling capacity and increase recyclingyields at plants (i.e. reduce recycling losses). (See Table A7)

Design for recycling is complex to model as it impacts many aspects of the value chain. To simplify the modelling approach of design for recycling implementation, three distinct modelling features were included. Note that b) and c) reinforce other effects such as higher investments in advanced technology:

a) Shift from multimaterials product category to flexible monomaterials. (i.e. substitution of multi-layered PE/PP packaging with multi-layered PE packaging). As industry is embracing circularity the share of 'hard-to-recycle' multimaterial will necessarily decrease to meet commitments;
b) Increase sortation yield (indirect effect). As the products become fit for purpose and designed with end-of-life in mind, sorting technologies are more likely to capture them (i.e. black pigments) or new market will open-up (i.e. if higher quality material can be obtained);
c) Increase recycling yield (indirect effect). As products become fit for purpose and designed with end-of-life in mind, the number of rejects/impurities in the recycling streams is likely to decrease (i.e. less residual PVC, similar pigments for PET bottles) leading to higher recycling yields overall.

IN THE CIRCULARITY SCENARIO, COLLECTION AND DESIGN FOR RECYCLING ASSUMPTIONS ARE ASSUMED TO INCREASE COMPARED TO CURRENT ACTIONS WHILE SORTING LOSSES DECREASE

Variable	ID		2020	2030	2040	2050	Comments and source
D4R: Shift from Multi to Rigid	Box 0.4.1	MLMM to Rigids	0%	25%	35%	35%	Increase in 2040 compared to Current Actions to match 90% shift in 2040 (10% increase in model)
D4R: Shift from Multi to Flexible	Box 0.4.2	MLMM to Flex	0%	26%	41%	41%	Increase in 2040 compared to Current Actions to match 90% shift in 2040 (15% increase in model)
D4R: Shift from flex to rigid	Box 0.4.2	Flex to rigid	0%	0%	1%	1%	Breaking the Plastic Wave (SYSTEMIQ)
EMF: Shift from Multi to Flexible	Box 0.1.4	MLMM to Flex	0%	14%	14%	14%	EMF Global Commitment (pro-rated for Europe) – Same as CA
Waste formal collected for recycling (separated at source)	C1	Bottles	64%	90%	90%	90%	Same as Current Actions; maximum collection rate assumed to be achieved in 2030 already
Waste formal collected for recycling (separated at source)	C1	Rigid	42%	75%	80%	85%	2030 as Current Actions; 2040 and 2050 team assumption for 'target states' of collection for recycling
Waste formal collected for recycling (separated at source)	C1	Flexible	38%	60%	70%	80%	2030 as Current Actions; 2040 and 2050 team assumption for 'target states' of collection for recycling
Waste formal collected for recycling (separated at source)	C1	MLMM	0%	0%	0%	0%	Same as BAU and Current Actions
Share sorted waste to closed loop	F1	Bottles	49%	57%	66%	77%	Simulating an increase to 50% recycled content for beverage bottles (Pepsi); based on 1)
Share sorted waste to closed loop	F1	Rigid	31%	39%	51%	65%	Target state from 5) BPW but for 2050 instead of 2040 as lower starting point
Share sorted waste to closed loop	F1	Flex	34%	42%	53%	66%	Simulating an increase to 40% recycled content for films; based on 2)
Share sorted waste to closed loop	F1	MLMM	0%	0%	0%	0%	
Share sorted waste to losses	F3	Bottles	15%	9%	5%	5%	3) Antonopoulos et al. (2021): 2030 scenario and best practice MRF5 as 2040 target
Share sorted waste to losses	F3	Rigid	25%	16%	10%	10%	2030 scenario from 3) Antonopoulos et al. (2021) and 2040 target based on 4) UK Wrap (2019)
Share sorted waste to losses	F3	Flex	41%	27%	17%	11%	3) Antonopoulos et al. (2021): 2030 scenario and best practice MRF5 as 2050 target
Share sorted waste to losses	F3	MLMM	100%	100%	100%	100%	
Share sorted waste to open loop	F2	All categories	1-F1-F3	1-F1-F3	1-F1-F3	1-F1-F3	Plug number: 100% - Closed loop recycling – Sorted waste to losses

Source: 1) PRE (2020): PET Market in Europe – State of Play; 2) PRE (2020): Flexible Films Market in Europe - State of Play; 3) Antonopoulos et al. (2021): post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers ; 4) UK Wrap (2019): PlasticFlow 2025: Plastic packaging flow data report; 5) SYSTEMIQ & Pew Charitable Trust (2020): Breaking the Plastic Wave: A Comprehensive Assessment of Pathways Towards Stopping Ocean Plastic Pollution

IN THE CIRCULARITY SCENARIO, ACTUALLY RECYCLED OUTPUT INCREASES WHILE RECYCLING LOSSES DECREASE BASED ON DESIGN FOR RECYCLING AND NEW TECHNOLOGY INVESTMENTS

Variable	ID		2020	2030	2040	2050	Comments and source
Share of closed loop actually recycled	I1	Bottles	81%	91%	91%	91%	Target state 2030 as per Antonopoulos 2021 (2030 scenario); assumed to plateau at this point
Share of closed loop actually recycled	I1	Rigid	78%	87%	87%	87%	Target state 2030 as per Antonopoulos 2021 (2030 scenario); assumed to plateau at this point
Share of closed loop actually recycled	I1	Flex	55%	70%	79%	86%	Target state 2050 as per Antonopoulos 2021 (best practice REC)
Share of closed loop actually recycled	I1	MLMM	0%	0%	0%	0%	No recycling for MLMM
Share of closed loop to losses	I2	Bottles	19%	9%	9%	9%	Target state 2030 as per Antonopoulos 2021 (2030 scenario); assumed to plateau at this point
Share of closed loop to losses	I2	Rigid	22%	13%	13%	13%	Target state 2030 as per Antonopoulos 2021 (2030 scenario); assumed to plateau at this point
Share of closed loop to losses	I2	Flex	45%	30%	21%	14%	Target state 2050 as per Antonopoulos 2021 (best practice REC)
Share of closed loop to losses	I2	MLMM	100%	100%	100%	100%	No recycling for MLMM
Same assumed for Share of open loop actually recycled (J0) + Share of open loop to losses (J1)							

Source: 1) Antonopoulos et al. (2021): post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers

Construction

In the construction sub-system, the mechanical recycling levers encompass

1. Expand separate collection of plastic waste: modular design to facilitate dismantling and separate collection of plastic at end of life; (see Figure A18)
2. Expand sorting: Maximise recovery of plastic in both on and off-site sorting; (see Figure A19)
3. Design for recycling: Maximise recycling rates through simplicity of polymer, colouring, labelling etc. and increase quality of recyclate; (see Figure A20)
4. Increase uptake of mechanically recycled content: Expand closed loop recycling through improving the quality of recycled plastic. (see Figure A21)

LEVER 1: PLASTIC WASTE SENT TO SORTING FROM C&D INCREASES FROM ~30% TODAY TOWARDS A MAXIMUM OF ~64% AS A RESULT OF MODULAR DESIGN AND THE ENFORCEMENT OF SEPARATE COLLECTION OBLIGATIONS

Driving assumption

- **Overall separate collection rate increases towards a maximum of ~64%, based on the EEA's estimate of maximum separate collection rates of total C&D waste.** [1]
- **Polymers which are present in larger volumes e.g. PVC and polyolefins have higher recovery rates, particularly through targeted schemes e.g. Recovinyl.**

Supporting factors

- Stricter enforcement of pre-demolition audit requirements, increased use of material passports and, in later years, modular building design enables non-destructive dismantling and recovery of separate materials.
- Likely to be supported by policy e.g. material-specific recovery targets and mandatory recycled content targets - according to the EU commission, separate collection of plastic waste will reach 'very high' levels by 2030.

Limiting factors

- Embedded in building structure e.g. flooring, insulation in walls etc.
- Makes up only ~0.5% of total C&D waste so extraction from demolition matrix makes recovery difficult
- Low material value at present makes recovery uneconomic
- currently, only half of the MSs and the UK have separate collection obligations for specific materials and these are rarely enforced[2].

Impact on system stocks and flows

Share of waste sent for sorting/reuse (Arrow C1 + C3)	2020	2030	2040	2050	Rationale/Assumption
PVC	47%	56%	77%	80%	2030 value governed by VinylPlus target and 2050 set by maximum separate collection rate of 80%.
Polyolefins	30%	40%	61%	64%	Assume that separate collection rates increase at same rate as PVC, in line with EEA estimates.
Styrenics	13%	22%	43%	46%	Assume that separate collection rates increase at same rate as PVC, in line with EEA estimates.
Other	12%	15%	20%	20%	Separate collection of 'other' is limited to 20% as absolute volume needs to be high enough to justify it.

Source:
1) EEA (2020) The case for increasing recycling: Estimating the potential for recycling in Europe.
2) Deloitte (2017) *Resource Efficient Use of Mixed Wastes - Improving management of construction and demolition waste*

LEVER 2: TECHNOLOGICAL SOLUTIONS INCLUDING ROBOTIC SORTING REDUCE SORTING LOSSES OF PLASTIC WASTE FROM CONSTRUCTION AND DEMOLITION TO A MINIMUM OF10%

Driving assumption

- **Sorting losses decrease at steady rate due to the adoption of improved sorting technologies e.g. robotic sorting towards a min. of 10% as achieved by Finish ZenRobotics.**
- **The current technical barriers of sorting are overcome when materials which reach a 50%/60% separate collection threshold.**
- **Styrenics and other polymers are present in lower volumes so recovery rates are lower.**

Supporting factors

- Scaling up new automated sorting technologies and solutions such as robotic sorting could allow for more efficient and effective sorting as demonstrated by ZenRobotics.
- European Strategy for Plastics recommends that by 2030 sorting capacity is increased fourfold therefore regulatory pressures are likely to incentivise the adoption of such technological solutions.[2]

Limiting factors

- Poor economics due to low value of material and low relative volumes.
- Legacy additives, particularly for PVC (cadmium and lead), and for insulation materials (flame retardants such as HBCD)

Impact on system stocks and flows

Sorting losses (F3)	2020[3]	2030	2040	2050	Rationale/Assumption
PVC	27%	25%	10%	10%	Separate collection rates exceed 60% by 2040 so sorting losses are reduced to a minimum of 10%
Polyolefins	20%	19%	10%	10%	Separate collection rates exceed 60% by 2040 so sorting losses are reduced to a minimum of 10%
Styrenics	35%	33%	22%	19%	Low separate collection rates only allow for a steady decrease in sorting losses which remain above the minimum.
Other	35%	33%	22%	19%	Low separate collection rates only allow for a steady decrease in sorting losses which remain above the minimum.

Source: 1) Collectors 2020 Construction and demolition waste (CDW) » Collectors (collectors2020.eu) 2) EU Commission (2018) European Strategy for Plastics in a Circular Economy 3) Antonopoulos et al. (2021) *Recycling of post-consumer plastic packaging waste in the EU: recovery rates, material flows and barriers*

LEVER 3: DESIGN FOR RECYCLING HAS MINIMAL IMPACT ON RECYCLING RATES BY 2050 DUE TO IN-USE LIFETIME LAG OF PRODUCTS

Driving assumption

- **Recycling losses decrease towards a minimum of 15%as a result of design for recycling e.g. through simplicity of polymer, colouring, labelling etc.**
- **Calculated based on a lifetime probability distribution with a mean of ~35 years hence minimal effect seen in a 30 year period.**
- **Styrenics achieve lower recycling rates due to challenges associated with high-quality mechanical recycling of styrene.**

Supporting factors

- Mandatory recycled content requirements likely to be introduced as part of the CEAP which incentivises producers to design for recycling in order to increase recycling rates
- Construction plastics are often not visible (e.g. pipes, insulation etc.) so aesthetic requirements are not limiting.

Limiting factors

- Additives such as fillers and flame retardants make design for recycling challenging.
- Lifetime lag means effect is minimal before 2040.

Impact on system stocks and flows

Recycling losses (I2,J1)	2020[1]	2030	2040	2050	Rationale/Assumption
PVC	20%	20%	19%	18%	Recycling losses decrease towards a minimum of 15%.
Polyolefins	22%	22%	21%	19%	Recycling losses decrease towards a minimum of 15%.
Styrenics	34%	34%	32%	28%	Recycling losses decrease towards a minimum of 15%.
Other	30%	30%	29%	26%	Recycling losses decrease towards a minimum of 15%.

Source: 1) Antonopoulos et al. (2021) *Recycling of post-consumer plastic packaging waste in the EU: recovery rates, material flows and barriers*

LEVER 4: DESIGN FOR RECYCLING AND INCREASED DEMAND FOR MECHANICALLY RECYCLED CONTENT INCREASES THE SHARE OF CLOSED-LOOP RECYCLING FROM 40% TODAY TO 65% BY 2050

Driving assumption

- **Share of closed loop mechanical recycling is assumed to increase to match the increasing demand for recycled content[1].**
- **Low volumes and challenges associated with recycling Styrenics limits recyclate quality and thus limits share of closed-loop recycling to 10%.**

Supporting factors

- New CEAP is likely to introduce mandatory recycled content requirements, incentivising design for recycling to ensure high quality recyclates.
- Certain applications in the construction sector show good potential for uptake of recycled content (e.g. insulation materials, pipes etc.).
- The production of recyclate is tightly bound to the trend of the renovation ratio. The trend towards renovation means a higher amount of post-consumer waste would be available, thus increasing the potential for closed-loop recycling.

Limiting factors

- High quality plastic recycling is held back by insufficient volumes and quality of separate collection and sorting.
- Legacy additives which are no longer permitted (e.g. cadmium and lead in PVC) restrict the amount of plastic that can be recycled in closed loops.

Impact on system stocks and flows

Share of closed-loop mechanical recycling (F1/(F1+F2))	2020[2,1]	2030	2040	2050	Rationale/Assumption
PVC	100%	100%	100%	100%	Already closed-loop.
Polyolefins	25%	50%	75%	80%	Steady increase in share of closed loop recycling to 80% by 2050. No technical limits on recycled content.
Styrenics	0%	5%	28%	50%	EPS mechanically recycled into XPS. Increases as separate collection rates increase.
Other	0%	0%	0%	0%	Insufficient volumes limits closed-loop.

Source: 1) Watkins, E. et al. (2020) Support to the Circular Plastics Alliance in establishing a work plan to develop guidelines and standards on design-for recycling of plastic products 2) VinylPlus (2020) Progress Report 2020

Automotive

In the automotive sub-system, the mechanical recycling levers encompass

1. Reduce leakage out of the system: Maximise formal collection of vehicles by ATFs. Stricter enforcement of ELV directive and EPR systems.; (see Figure A22)
2. Design for dismantling: Designing vehicles from inception to facilitate dismantling at end of life; (see Figure A23)
3. Scale-up advanced Post-shredder technologies and design for PST: Maximise use of advanced post-shredder technologies and increase recovery of plastics from shredder residue. (see Figures A24-A26)
4. Design for recycling: maximise recycling rates through simplicity of polymer, fewer fillers and additives and fewer polymer types etc. (see Figure A24)
5. Increase quality of mechanical recyclate: Expand closed loop recycling by improving the quality of recycled plastic and forming supply chain partnerships. (see Figure A26)

LEVER 1: LEAKAGE OUT OF THE SYSTEM VIA ILLEGAL EXPORTS AND TREATMENT IN UNAUTHORISED FACILITIES IS REDUCED TO NEGLIGIBLE LEVELS BY 2040

Driving assumption

- **Stricter enforcement of the ELV directive resulting in a 75% reduction in illegal treatment by 2030, increasing to 90% by 2040.**
- **Illegal exports are reduced to 0% by 2040 resulting in a 50% reduction in overall exports.**

Supporting factors

- Inception Impact Assessment of ELV Directive[1] carried out last year highlights illegal exports and illegal treatments as key issues which are likely to be dealt with more strictly in the revision of the ELV Directive.
- Strengthening EPR systems and scaling up new technological solutions could allow for better traceability of ELVs.
- OEMs increasingly involved in end-of-life vehicle collection (e.g., discounts for guaranteed returns, deposits).

Limiting factors

- Current version of the Directive also banned exports of ELVs and required that ELVs are treated in ATFs only but has failed to be enforced so greater enforcement needed along with stricter policy.
- Lack of consistent definition of ELV across member states results in higher levels of exports

Impact on system stocks and flows

All plastic categories	2020[2]	2030	2040	2050	Rationale/source
ELVs transferred to ATFs (Arrow A1)	59%	77%	83%	85%	1 – (A2 + A3 + A4)
Vehicles left on land (Arrow A2)	3%	3%	3%	3%	Assume no change in rate of abandoned vehicles
Vehicles treated at unauthorised facilities (Arrow A3)	17%	9%	4%	2%	Assume 90% reduction in illegal treatment
Vehicle exports (Arrow A4)	21%	15%	10%	10%	Assume no illegal exports by 2030 but legal exports remain.

Source: 1) EC (2020) Inception Impact Assessment - Revision of Directive 2000/53/EC on end-of-life vehicles 2) Mehlhart et al. (2017) *Assessment of the implementation of Directive 2000/53/EU on end-of-life vehicles (the ELV Directive) with emphasis on the end-of-life vehicles of unknown whereabouts.*

LEVER 2: DESIGN FOR DISASSEMBLY OF VEHICLES INCREASES THE RECOVERY OF PLASTIC COMPONENTS PRIOR TO SHREDDING FROM 4% TODAY TO 15% BY 2050

Driving assumption

- **Under best known practices, around 10%-11% of total plastic can be dismantled with current designs[1]. Assume 90% adoption of best practice by 2030.**
- **Further improvement beyond 2030 comes from design for disassembly which increases the share that can be dismantled to 15%**
- **Minimal change before 2040 due to in-use lifetime lag before which design for dismantling has little effect.**

Supporting factors

- The specific topics of the roadmap for revising the ELV Directive regarding plastics includes, specifically, the dismantling of plastic parts.
- Mandatory recycled content requirements of plastic components in vehicles will incentivise design for disassembly to improve recoverability of plastic.

Limiting factors

- Plastic recovery by manual dismantling remains marginal because of poor economics driven by high costs, low prices of secondary plastics and time constraints. Automatized dismantling is hindered by the diversity and composite structures of car components.
- While dismantling of bumpers is currently possible, it is rare given the lack of necessary channels to support reuse and recycling.

Impact on system stocks and flows

Share of plastic dismantled (Arrow C2)	2020[2,3,4]	2030	2040	2050	Rationale/source
Bumpers and Fuel tanks	14%	50%	90%	90%	90% of large plastic components dismantled by 2040
Other Polyolefins	4%	4%	6%	10%	Dismantling rates increase incrementally through design for recycling but economics and storage/time constraints remain.
Other polymers	2%	2%	3%	4%	Dismantling rates increase incrementally through design for recycling but economics and storage/time constraints remain.

Source: 1) CPA (2020) Auto – Collection and Sorting SoP2) EUROSTAT (2021) *End-of-life vehicles by waste management operations 3)* Kawecki et al. (2018) *Probabilistic Material Flow Analysis of Seven Commodity Plastics in Europe.* 4) Monier et al. (2019) *Annual Report the End-of-Life Vehicle observatory – 2017 data*

LEVER 3/4: DESIGN FOR RECYCLING AND THE SCALING UP OF POST-SHREDDER TECHNOLOGY CAPACITY INCREASES THE AVERAGE SHARE OF PLASTIC RECOVERED FOR MECHANICAL RECYCLING FROM SHREDDER RESIDUE FROM 13% TODAY TO 50% BY 2050

Driving assumption

- **A large expansion of advanced post-shredder technology across the EU + UK to achieve levels of recovery equivalent to best practice today by 2040[1,2].**
- **Beyond 2040 a marginal improvement is assumed as a result of PST technology improvements and design for recycling i.e. fewer polymer types, simplicity of polymer, fewer composites etc.**

Supporting factors

- EU directive on end-of-life vehicle recycling to be revised with focus on mandatory recycled content for certain components and improved recycling efficiency.
- Scaling up of new technologies e.g. airflow technology and electrostatic separation techniques could improve recycling yield.
- OEMs setting targets on recycled content and forming supply chain partnerships with recyclers increases demand for PST capacity.

Limiting factors

- Separation technologies such as float-sink tanks and laser and infra-red systems are extremely costly. The economics of advanced PST are poor particularly with low prices of secondary plastics.
- 39 different polymer types and plastics with overlapping densities make separation very difficult.

Impact on system stocks and flows

Post-shredder losses (F3)	2020[3,4,5]	2030	2040	2050	Rationale/source
Bumpers and Fuel tanks	76%	69%	42%	40%	Recovery rates increase as Advanced PST capacity expands and design for recycling improves recovery.
Other Polyolefins	76%	69%	42%	40%	Recovery rates increase as Advanced PST capacity expands and design for recycling improves recovery.
Other polymers	98%	90%	60%	58%	Recovery rates increase as Advanced PST capacity expands and design for recycling improves recovery.

Source: 1) BKV Ramboll (2020) *Summary of Plastic Parts from ELVs 2) Circular Plastics Alliance (2021)* Automotive WG input for Deliverable 2: Work Plan on State of Play Collection and Sorting 3) EUROSTAT (2021) *End-of-life vehicles by waste management operations 4)* Kawecki et al. (2018) *Probabilistic Material Flow Analysis of Seven Commodity Plastics in Europe.* 5) Monier et al. (2019) *Annual Report the End-of-Life Vehicle observatory – 2017 data*

LEVER 3: DESIGN FOR RECYCLING ENABLES RECYCLING LOSSES TO DECREASE TO A MINIMUM OF 15%

Driving assumption

- **Recycling losses decrease to a minimum of 15% by 2050 as a result of products designed for recycling e.g. through simplicity of polymer, fewer polymer types and fewer additives and fillers.**
- **Minimal effect up to 2050 due to in-use lifetime lag.**
- **Other polymers achieve lower recycling rates due to composite structures and diversity of polymer types.**

Supporting factors

- Mandatory recycled content requirements are likely to be introduced which incentivises design for recycling to ensure a high-quality supply of recyclates.
- Purer plastics streams as dismantling increases and PST technologies are improved.

Limiting factors

- Currently, 39 different polymers used in vehicles which are highly customised, contain lots of additives and have similar densities making recovery from shredder residue very difficult.
- Growing use of reinforced plastics containing fillers that are almost impossible to recycle.
- 10-20 years of exposure to wear and tear, UV and chemicals hinders high-quality mechanical recycling.

Impact on system stocks and flows

Recycling losses (Arrow I2/ J1)	2020[1]	2030	2040	2050	Rationale/source
Bumpers and Fuel tanks	25%	24%	18%	15%	Recycling losses reach minimum of 15% by 2040.
Other Polyolefins	25%	24%	18%	15%	Recycling losses reach minimum of 15% by 2040.
Other polymers	28%	27%	23%	20%	Recycling losses to decrease to 20% by 2050.

Source: 1) Antonopoulos et al. (2021) *Recycling of post-consumer plastic packaging waste in the EU: recovery rates, material flows and barriers*

LEVER 3/5: INCREASED UPTAKE OF MECHANICALLY RECYCLED CONTENT AND DESIGN FOR RECYCLING DRIVES AN INCREASE IN THE SHARE OF CLOSED-LOOP RECYCLING

Driving assumption

- **Share of closed-loop recycling increases at same rate as recycled content targets recommended by EuRIC.[1] These targets are based on existing commitments made by OEMs.**
- **By 2050, recycled content reaches 50% (on average), following the trajectory of the EuRIC targets.**

Supporting factors

- OEMs testing short looping of raw materials via supply chain partnerships (e.g., Renault, Ford) which is likely to drive improvements in the share of closed-loop recycled content
- Mandatory recycled content requirements likely to be introduced.
- A growing number of publicly stated corporate commitments to use recycled content (e.g., Volvo aims for 25% by 2025).

Limiting factors

- In many cases, the availability and quality of recycled plastics is relatively uncertain.
- In the automotive sector, there is a culture of quality and a reluctance to do things that would impact their real sense of the quality of the product. As polymers evolve closed loop recycling is challenging as the same polymers physical properties change to meet newer designs and processing equipment, e.g. MFI
- Strict specifications for products which do not allow for the use of recyclates which may contain legacy additives.

Impact on system stocks and flows

Share of closed-loop out of total mechanical recyclate produced	2020[2]	2030	2040	2050	Rationale/source
Bumpers and Fuel tanks	13%	53%	63%	78%	Share of closed-loop recycling increases at same rate as recycled content targets recommended by EuRIC
Other Polyolefins	8%	51%	61%	76%	Share of closed-loop recycling increases at same rate as recycled content targets recommended by EuRIC
Other polymers	5%	8%	18%	23%	Share of closed-loop recycling increases at same rate as recycled content targets recommended by EuRIC

Note that this does not include recyclate coming from other sectors. We also assume 20%[3] of recyclate from mono-rigid packaging to contribute to recycled content in vehicles. It also does not include chemical recycling.

Source: 1) EuRIC (2019) *Position paper: Call for recycled plastic content in cars* 2) WRAP, 2019. Plastics Market Situation Report. 3) Watkins, E et al. (2020) Support to the Circular Plastics Alliance in establishing a work plan to develop guidelines and standards on design-for-recycling of plastic products

System Intervention #4: Chemical Recycling

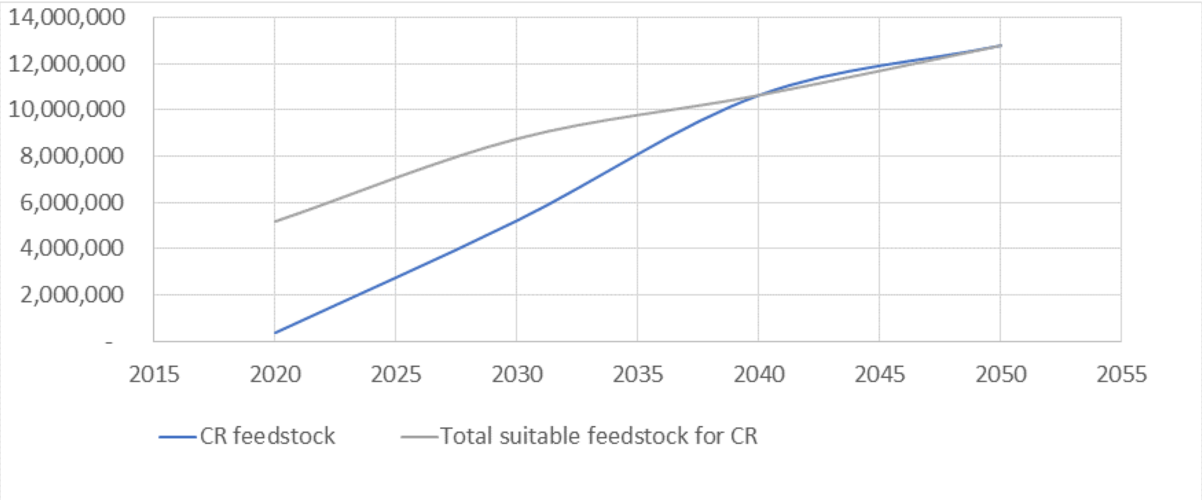
While the model differentiates between 4 types of chemical recycling, (dissolution, depolymerisation, pyrolysis and gasification) all types have been grouped together into a single lever.

Market growth

- Constrained either by feedstock availability or market growth – there is a different amount of feedstock available per scenario driven by a range of earlier assumptions around growth, policy impact, reduction & substitution and mechanical recycling, thus calculation must be dynamic per scenario.

- We assume that PlasticsEurope commitments define market growth until 2030 (1.2 Mt of recyclate by 2025 and 3.4 Mt by 2030) and thus these values were interpolated. Following the peer-reviewed methodology of Breaking the Plastic Wave, a proxy market growth rate of 5% was assumed based on the long-run average of the ethanol industry in Brazil in the three decades following the decade of major market expansion. We therefore assume an S-curve ramp up to **13.9 Mt** of feedstock into chemical recycling by 2050 (yielding ~8Mt of recyclate).
- The smaller of the two constraints defines the actual growth of total chemical recycling.

Recycling scenario growth:



Suitable feedstock and allocation to sectors

- We assume the waste streams that are available for chemical recycling are: 1) mixed waste 2) losses from formal sorting 3) recycling losses (and in the case of automotive, automotive shredder residue and WEEE).
- We assume that 95% of the waste from formal sorting losses and recycling losses are suitable for chemical recycling while only a smaller proportion of the waste from mixed streams are suitable for chemical recycling due to contamination driving uneconomical corrosion within facilities (10% increasing to 50% by 2050 to reflect the growth of gasification)
- Allocations to sectors and waste streams is weighted by the volume of waste coming from each waste stream and the suitability of that waste stream to chemical recycling i.e. if 10% of suitable feedstock for chemical recycling is from mixed consumables waste, 10% of total chemical recycling is allocated to this waste stream.
- As a result of this allocation method, **70%-80%** of CR feedstock is from consumables, **15%-20%** from automotive and **5%-10%** from construction.

Chemical recycling pathway evolution to 2050

- The blend of chemical recycling technologies is a highly uncertain and contentious assumption, and one that should not be used as a basis for investment decisions or seen as a forecast. The Expert Panel on this report advised that selecting a mix of chemical recycling technologies would more accurately illustrate the costs, material losses and GHGs across the systems.

- Therefore, a mix was assumed based on the current state of market investment, technology feedstock tolerance, waste availability in a system where chemical recycling is complementary to mechanical recycling.
- We assume Pyrolysis is the front runner in the 2020s with a share of 50%. The share then decreases due to the high emissions of pyrolysis and is surpassed by gasification by 2040.
- Share of depolymerisation and depolymerisation is driven by the availability of suitable polymers and high purity waste streams.
- As these technologies mature, these constraining factors will likely change, but constitute the most credible mix that could be assumed at the time of writing.

Additional levers: macro GHG reduction levers

- We have cultivated the following levers for the GHG scenario.

    - **Steam Crackers + CCS:** we have assumed that direct pipes to port and then oil-field are required for steam cracker + CCS. Shipping of CO2 is not included. Therefore, crackers within a 100km proximity of a North Sea facing industrial hub are viable for CCS

    - **Incinerators + CCS:** the same geographic principle is applied to incinerators as to crackers. However, incinerators are much greater in number (500+ vs ~80 crackers in 45 locations in Europe) and geographically dispersed. CCS is dependent upon the growth of industrial clusters (requiring significant government subsidy) thus proximity to these clusters near the North Sea is a limiting factor. Furthermore, the capex required for capture and transportation to the cluster is a limiting factor vs crackers. The likelihood of this market achieving significant scale before 2040 is limited, and thereafter is only applicable to the proportion of incinerators within 100km of an industrial cluster.

    - **Green H2 Steam Crackers + By Products Upgrade:** retrofitting a virgin fossil steam cracker with hydrogen fuel is deemed by experts not to be an overly complex process with relatively manageable capex expenditure (vs e.g. an electric steam cracker). There are examples of grey hydrogen fired furnaces in existence thus there is precedent from a technical perspective. There are three major issues with this concept

        1) the by-products (e.g. methane) in a traditional steam cracker are used to fuel the cracker itself, some of which would drive emissions. To overcome this problem, two options were available i) sell the by-products and ii) upgrade the by-products themselves into plastics. We have assumed the market for these by-products declines over time in a decarbonising world thus option ii) was modelled e.g. by methane > methanol > olefins (MTO route). This results in a larger volume of product and thus revenue deriving from the traditional input volume of naphtha for a tonne of polymer, but also higher costs. Tertiary emissions from this process as assumed to remain in as scope three and no tertiary upgrade process is assumed.

        2) Green H2 is currently expensive. We have assumed that blue Hydrogen is less efficient than just applying CCS to steam crackers directly, and furthermore our view is that while blue hydrogen may be more economical in the short term, Green becomes more economical from 2030. However, the volume of green

hydrogen production is expected to be very low even during the 2030s, only scaling significantly during the late 2030s and reach major commercial scale from 2040. Plastic is less likely to be the key driver for the scaling of the Green Hydrogen market. For this reason, even if the price drops, its lack of ubiquity mean it can only be applied selectively to crackers near to industrial clusters where there is an abundance of affordable renewable energy.
3) Green H2 is also may face scaling and volume constraints until the 2040s with competition over renewable electrons. Therefore, there is a scarcity Green H2 across Europe until transportation and storage infrastructure has been developed, and multiple H2 production hubs have been grown. We have assumed that southern Europe has excellent solar and wind capabilities, and that the UK and North Sea areas have excellent offshore wind capabilities conducive to Green Hydrogen production. Similarly, the Nordics, particularly, Sweden, have excellent hydro and biomass resources, thus also have good access to Green Hydrogen, leaving northern, less renewables abundant European geographies with selective opportunity for green H2 access

- In addition to this, we have cultivated the following levers for the Net Zero Systems Change Scenario:

    - **Biomass:** The business case for the application of biomass is challenging until 2040 due to the cost of green hydrogen, thus it is a very expensive option for shifting from virgin fossil feedstock and there are sustainability constraints upon the annual market size (6-7Mt of polymer). Therefore, Biomass is considered a plug of a limited size to reach Net Zero in the NZSCS.

    - **Electric Steam Crackers (ESC) + by products upgrade:** Capex is assumed to be high for the ESC but with much lower opex vs H2 crackers. R&S and recycling mean total demand for virgin steam cracking is significantly reduced in later scenarios, thus ESC is only applied selectively where older, smaller, less efficient crackers are decommissioned and replaced with greenfield sites (2-3 max new crackers in the RISCS by 2050). Furthermore, ESC may present several technical challenges which mean its TRL vs hydrogen fired furnaces is lower. We have assumed the ESC will not be powered off grid. Beyond the technical application of electricity in high-temperature industrial processes, the cyclicality of renewable electricity for a 24/7/365 cracker process presents issues given night-time lags in production and risks of cloudy weeks during winter etc. Storage and transmission may/may not overcome some of these, but even if they do the cost efficiency vs H2 might be a challenge.

    - **Incineration + CCU > CO2+H2:** For incinerators where CCS is not available (%), assuming that massive CO2 transportation infrastructure is not developed across Europe, there are still major carbon emissions that keep the European Plastics System substantially above net zero emissions. In order to close this gap, incinerators not geographically near to a form of carbon storage need to capture their carbon and make use of it. The use of carbon in products is a more nascent technology than CCS, and there are limited examples of where this is applied in practice. However, we are facing a future where there is likely an abundance of CO2 from industries decarbonising, thus the plastics system can consider both a closed carbon cycle (plastics to carbon to plastics) vs an open carbon cycle where captured carbon from end of life can be sold to other sectoral uses as well as bought from other sectors for use as plastics. Given the uncertainty around this space, we have restricted this pathway to the recycling of carbon from the plastics sector – we have considered that the plastics industry will take accountability for its absolute carbon emissions to reach net zero, and thus can control both the supply and demand side levers to manufacture this pathway. Thus, the size of this pathway is driven by the availability of captured carbon from incineration following optimised R&S and recycling. We have optimistically assumed this is the market constraint, coupled with the additional "polymer opportunity" as defined by the Global CO2 Initiative. Similar to H2 crackers, this opportunity is also constrained by the prevalence of green H2 economically until 2030 and geographically until 2040. This lever thus acts in tandem with Biomass to create a plug that displaces the virgin fossil production where GHGs cannot be reduced to drive towards net zero but at a high cost.

- **GHG reduction levers applied to chemical recycling:** we have avoided compounding levers between groups (GHGs, Recycling and R&S) but given the emissions level of pyrolysis, should this route be taken as a dominant CR pathway, it would result in significant system emissions by 2050. In effect, Pyrolysis only abates incineration emissions, and is assumed to be on par with virgin production. Therefore, we have assumed similar application of CCUS and electrification to this process with an abatement curve based on the broader virgin production abatement curve, applied only to Pyrolysis. We believe this is a pre-requisite for pyrolysis and also note the associated capex lock in issues with pyrolysis to virgin steam crackers.

Retrofit Systems Change Scenario:

		2020	2030	2040	2050
Electric steam cracker	%	0%	0%	0%	0%
H2 Steam cracker + by products upgrade	%	0%	1%	14%	36%
Steam cracker + CCS	%	0%	11%	34%	33%
Conventional Steam cracker	%	100%	88%	51%	31%

Net Zero Systems Change Scenario:

		2020	2030	2040	2050
Electric steam cracker	%	0%	5%	8%	10%
H2 Steam cracker + by products upgrade	%	0%	1%	19%	55%
Steam cracker + CCS	%	0%	12%	34%	33%
Conventional Steam cracker	%	100%	83%	40%	2%

- Electric steam crackers introduced for new greenfield capacity and to replace small inefficient plants which are decommissioned.
- Alternative feedstock (biomass, CO2+H2) reduce the need for virgin fossil so there are even fewer conventional steam crackers remaining in 2050.

<u>**Incineration**</u>

Retrofit SCS - No CCU	2020	2030	2040	2050
Incineration	100%	95%	90%	84%
Incineration + CCS	0%	5%	10%	16%
Incineration + CCU	0%	0%	0%	0%

Net Zero SCS - CCU added	2020	2030	2040	2050
Incineration	100%	77%	31%	8%
Incineration + CCS	0%	5%	10%	16%
Incineration + CCU	0%	18%	59%	77%

- Limited potential for CCS due to geographic constraint of proximity to North Sea facing CCS cluster
- CCU introduced only in the NZSCS with much greater potential – **this is one of the most aggressive and uncertain assumptions in the analysis**

Alternative Feedstock

- Only in the NZSCS

Metric	2020	2030	2040	2050
Sustainable biomass plastics production [Mt/y]	0.0	1.3	2.6	4.0
CO2 + H2 plastics production [Mt/y]	0.0	0.8	2.0	3.0

Decarbonisation of Chemical Recycling

- NZSCS only
- Applied only to Pyrolysis and is in line with the decarbonisation of steam crackers (through H2, electric steam crackers and CCS)
- Other technologies decarbonise through macro-levers e.g. grid decarbonisation, process shift from natural gas to electricity and prevalence of green H2.

“ReShaping Plastics: Pathways to a Circular, Climate Neutral Plastics System In Europe” presents an evidence-based roadmap for a paradigm shift in the European Plastics system. Following the approach developed in *Breaking the Plastic Wave*, it quantifies the economic, environmental, and social indicators for six possible scenarios to achieve plastic circularity while significantly reducing greenhouse gas emissions in Europe.

A Steering Committee comprising 13 senior leaders from public policy, civil society and industry provided strategic guidance for this work, while a panel of 10 experts ensured the scientific accuracy of the study.

The aim of this report is to help guide policymakers, industry executives, investors, and civil society leaders as they seek to understand the trade-offs and navigate through a highly contested and complex terrain towards a circular Europe plastics system.

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