SYSTEMIQ

Circular PET and Polyester:

A circular economy blueprint for packaging and textiles in Europe

Technical appendix and detailed assumptions

"Circular PET and Polyester: A circular economy blueprint for packaging and textiles in Europe" – Technical appendix and detailed assumptions

This technical report compiles the methodology and assumptions underpinning the 'Circular PET and Polyester: A circular economy blueprint for packaging and textiles in Europe' report and its modelling. It is partly derived from two reports: the 'Reshaping Plastics' report published by Systemiq in 2022 and commissioned by Plastics Europe, as well as the 'Breaking the Plastic Wave' report published by Systemiq and The Pew Charitable Trusts in 2020 (along with the resulting peer-reviewed article 'Evaluating Scenarios Toward Zero Plastic Pollution' published in Science in July 2020). The focus of the main report is on clearly communicating the findings of the underlying model and analysis, with a deliberate attempt made to minimise explaining the process and assumptions of the analysis. However, in order to provide full transparency, this document provides a more detailed explanation of the approach taken to developing the model, the scenarios and respective key assumptions.

Contents

1. Introduction

The report provides a new evidence base, exploring future scenarios for the European Polyethylene Terephthalate (PET/Polyester[1]) sector and the extent to which complementary application of interventions across the entire value chain could contribute towards a circular, lower CO_2 emissions economy from 2020 to 2040. Interventions include a wide range of circular economy measures to slow consumption growth (PET elimination, product reuse and substitution with other advantageous materials), increases in waste collection and sortation as well as the application of chemical recycling (in the form of depolymerisation) alongside mechanical recycling for PET waste.

The findings of the report are based on the 'European PET/Polyester' model. This Technical Appendix transparently highlights the methodology and approach to the modelling as well as the scenarios constructed and corresponding key assumptions.

The 'European PET/Polyester' model projects stocks and flows of PET mass (in tonnes) across seven major PET product categories in the EU 27 countries plus the United Kingdom for the years 2020-2040. These stocks and flows of PET mass are quantified at different stages of the value chain in the system, as is the relationship between PET demand and recycled PET generated by the recycling of various waste PET products, as well as the interconnectedness between different product categories. Importantly, where products are typically comprised of PET and non-PET parts (such as the caps, lids and labels of PET bottles and the non-PET fibres in blended textiles that comprise PET as polyester and other fibres), or accumulate non-PET material (e.g. contamination during waste collection process), the weight of this non-PET material is discounted in order to track the flow of PET only within the model. This means that, for example, when recycling process yield rates are modelled, this on the basis of a 'PET-to-PET' yield rate. The product categories modelled (broadly: packaging and textiles) are explained in the section "PET categories". The model is shown in the system map in the section "System maps as basis for model".

Two core future scenarios are envisaged from 2020 to 2040: a 'Historical Trends Scenario', which is effectively used as the baseline for comparisons, and an 'Ambitious Complementarity Scenario', which examines the outcomes of scaling current, at-or-close-to commercial-scale, best-in-class technologies across Europe. The aim of the ambitious complementarity scenario is to understand the impact of these interventions on material circularity and system greenhouse gas (GHG; measured in tonnes of CO_2 equivalent) emissions. The projections under the 'Historical trends scenario' are based on the extrapolation of recent historic trend data (such as for European PET consumption, collection for recycling rates etc), where available and reasonable to do so. In addition to the two core scenarios, a number of sensitivities on the ambitious complementarity scenario have also been constructed. These are used to investigate which assumptions the model outputs are most affected by. A more complete explanation of the scenarios and sensitivities modelled is provided below in the section entitled 'Modelling principles, scenario construction and sensitivities overview'.

Scenarios have been modelled to establish potential pathways towards system circularity and reduction of GHG emissions. These scenarios are not forecasts, nor are they the only possible scenarios. They provide multiple views from an almost infinite number of potential

[1] Although the term 'Polyester' can refer to other non-PET polyesters, in the course of this work, it is only used to refer to polyester textiles where the polymer is PET specifically. Additionally, throughout this document, the acronym 'PET' maybe used without the '/polyester' appendage, but its meaning may be taken to include polyester textiles too, depending on the context.

scenario variations, in order to generate insights on different system change pathways, impacts and trade-offs.

Model limitations and uncertainty

The analysis assumes that major change is possible with adequate policy, behaviour change, financing, leadership, and technology adoption. Given the high level of uncertainty inherent in any exercise that takes a 20-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 (e.g. best-in-class performance may not scale accordingly across Europe for various reasons); the cost of certain technologies may vary significantly whilst required investments may not come to fruition; implementation of policies may not happen as expected (e.g., widespread adoption of deposit return schemes for bottles); currently-unforeseen technologies may grow rapidly to reach mass-adoption, which disrupt the existing outlook for the system; public discourse and behaviour change may result in completely different PET consumption patterns developing in future; development of international supply chains could change the economics of Europe pursuing high-circularity for all its PET waste; and potentially other factors.

The systems change levers modelled aim to establish the potential impacts of available technologies and operational capabilities to drive change in the PET system. Modelled scenarios were designed using the best available information to inform mass flows and greenhouse gas (GHG) emissions, yet the model does not capture all the components and complexity of the European PET system. Because gaps exist in data on all stages of the PET system (including the amount and type of PET products placed on the market, amount and sources of waste generation, collection, recycling, disposal, leakage of PET waste etc), 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 Europe-wide 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 highly circular, lower-emission PET system by analysing constraints and the potential for scaling of different interventions, based on historical trends and current developments. As such, this report seeks to understand what is possible and what factors this system vision depends upon.

Scientific rigour and diverse input

This analysis was conducted following a strict evidence-based approach, relying on reliable published data in conjunction with a Steering Group comprising 11 experts, representing diverse geographies and industries from across the value chain, as well as interviews and additional validation with further experts from across the PET/polyester sector. All assumptions and methodologies have been shared transparently and extensively peer-reviewed. They are available within this Technical Appendix.

Scope of study

Our analysis quantifies both the mass of PET flows and system GHG emissions across both consumer and industrial applications. The geographic boundary of the system map is the EU27+UK, due to availability of reliable historic data, except for the export of polyester textiles for reuse, for which the GHG emission footprint includes a weighted-average for the end-of-life fate of these textiles outside of Europe. The time interval for the modelling is 2020-2040, as this more closely-aligns with time horizons and targets as set out under relevant existing and draft EU policies involving the circular economy for packaging and textiles. Mass flows and emissions are quantified at the level of Europe and country-level dynamics were not modelled. System economics, as well as other environmental and health impacts, including those of (primary) microplastics or substances of concern, are not in-scope. The model begins with available data for PET consumption and is therefore thought to account for the vast majority of PET flows in Europe (waste data, for example, is known to be missing a significant volume of plastic waste when compared to consumption)[2]. The analysis covers PET packaging and polyester textiles. The import and export of both virgin PET and recycled PET are not considered in the model, and results are agnostic of their provenance and use.

PET product categories

The scope of this study covers 7.7 MT of total European PET demand, as of 2020, focusing on EU 27 countries plus the UK (EU27+UK). The analysis considers the two largest PET consuming sectors: packaging (62%) and textiles (38%) and models seven individual product categories across these sectors. More information on these sectors and the specific product categories modelled is provided below:

- **Packaging:** Given data availability, six separate packaging categories are modelled. These include clear beverage bottles, coloured beverage bottles, non-food-and beverage bottles, clear monomaterial pots, tubs and trays (PTTs) and multimaterial PTTs, as well as 'other packaging', thought to comprise mostly strapping and various types of PET films.
- **Polyester textiles**: this is modelled as a single product category, even though it constitutes 38% of PET consumption, due to the lack of reliable data on the exact product constitution of this category. However, available data indicates that the category is primarily comprised of clothing and household textiles, as well as a small proportion of industrial textiles (Table 1).

All references to PET/polyester in this report refer to these seven categories only, unless otherwise explicitly stated. Due to a lack of available data, pre-consumer PET waste flows (such as bottle production rejects and textile production offcuts) were not modelled separately and instead the mass of this material is assumed to be contained within the major mass flows of each product category. Additionally, PET used in other product categories beyond those modelled (such as electrical goods and the automotive sector) is excluded due to evidence of market shares for these applications constituting less than 1% of overall European PET consumption (Table 1) and as such these are not considered further, nor are possible future PET product categories that could gain significant market share in the next 20 years.

[2] ReShaping Plastics, Systemiq, 2022 ; Europe's Missing Plastics, Material Economics, 2022

TABLE 1: PET product categories, associated volumes, and data source

PET product categories	Mt of PET put on the EU market (2020) [(a)]	% of all PET put on the EU market (2020)
Clear food and beverage bottles	2.44 [(1) (b)]	32%
Coloured and opaque food and beverage bottles	0.66 [(1) (b)]	9%
Non-food and beverage bottles (clear, coloured & opaque)	0.16 [(1) (b)]	2%
Clear monomaterial pots, tubs and trays (PTTs)	0.41 [(1) (2) (c)]	5%
Clear multi-materialed PTTs	0.61 [(1) (2) (c)]	8%
Other packaging	0.49 [(1) (d)]	6%
Textiles	2.9 [(1) (3) (4) (5) (e)]	38%

Key points

- Product categories have been chosen primarily based upon availability of reliable data as to the proportion of the EU PET market they represent, as well as waste collection and recycling flows[(4)]. Other PET applications (e.g., automotive) are understood to constitute <1% of the total PET market and have been considered out of scope.
- Textiles have not been split into further categories as around 92% of polyester is understood to represent clothing and household textiles, with the remaining 8% being technical textiles where data is very poor[(5)].

Sources: (1) How circular is PET?, Eunomia and Zero Waste Europe (2022) (2) PET Market: State of Play 2022, Eunomia (2022), (3) Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate) (PET) Packaging Management Strategies in the EU, Andreasi Bassi, S., et.al (2022),(4) Probabilistic Material Flow Analysis of Seven Commodity Plastics in Europe, D. Kawecki et.al (2018), (5) Modeling the EU plastic footprint: Exploring data sources and littering potential, A. Amadei et.al (2022)

Figure notes: (a) It is recognised that PET consumption in 2020 may have been affected by the COVID-19 pandemic, but comparable historic data is not available to fully investigate and adjust for this.

(b) According to (1), 8% of the entire PET bottle market is 'non-beverage' (e.g. used for detergent, sauces ,toppings etc). Due to a lack of data around how this 8% breaks down across the different bottle colours, and limited evidence as to whether these non-food and beverage bottles are recycled differently, 4% of each of the clear and coloured bottle groups has been diverted to the 'Other bottles' category, on the assumption that half of the 8% are used in non-food-contact applications e.g. detergents.

(c) Due to lack of data, the extent to which PTT data includes non-food application such as cosmetics and pharmaceuticals, is not know, therefore all PTTs are considered to be food-grade. Additionally, due to lack of data and an assumed small market share, coloured/black PTTs are not modelled and so all PTTs are assumed to be clear. This is consistent with PTT market share data from (2).

(d) Comprised of PET strapping and film (which is understood to include various types). Durable goods excluded due to limited data availability.

(e) The European consumption estimate is understood to include textiles imports into Europe. Additionally, the EU textiles consumption figure is the centre point of data from sources (1) and (3).

System map

At the heart of the analysis is a conceptual mass-based model (Figure 1) that highlights the main stocks (represented by boxes in the system map) and flows (represented by arrows) of the above-mentioned PET/polyester product categories within the European system.

Effectively, the model is structured so that the mass flows of each product category remain separated and so conceptually there are seven separate system maps, one for each product category. The key point at which the product categories (and therefore the maps/model) connect together are when rPET, created through the recycling of PET waste in a given calendar year between 2020-2040, is pooled together by grade and then subsequently allocated to the production of new PET products in the next year. The choice of how this rPET is divided up between products will be discussed later.

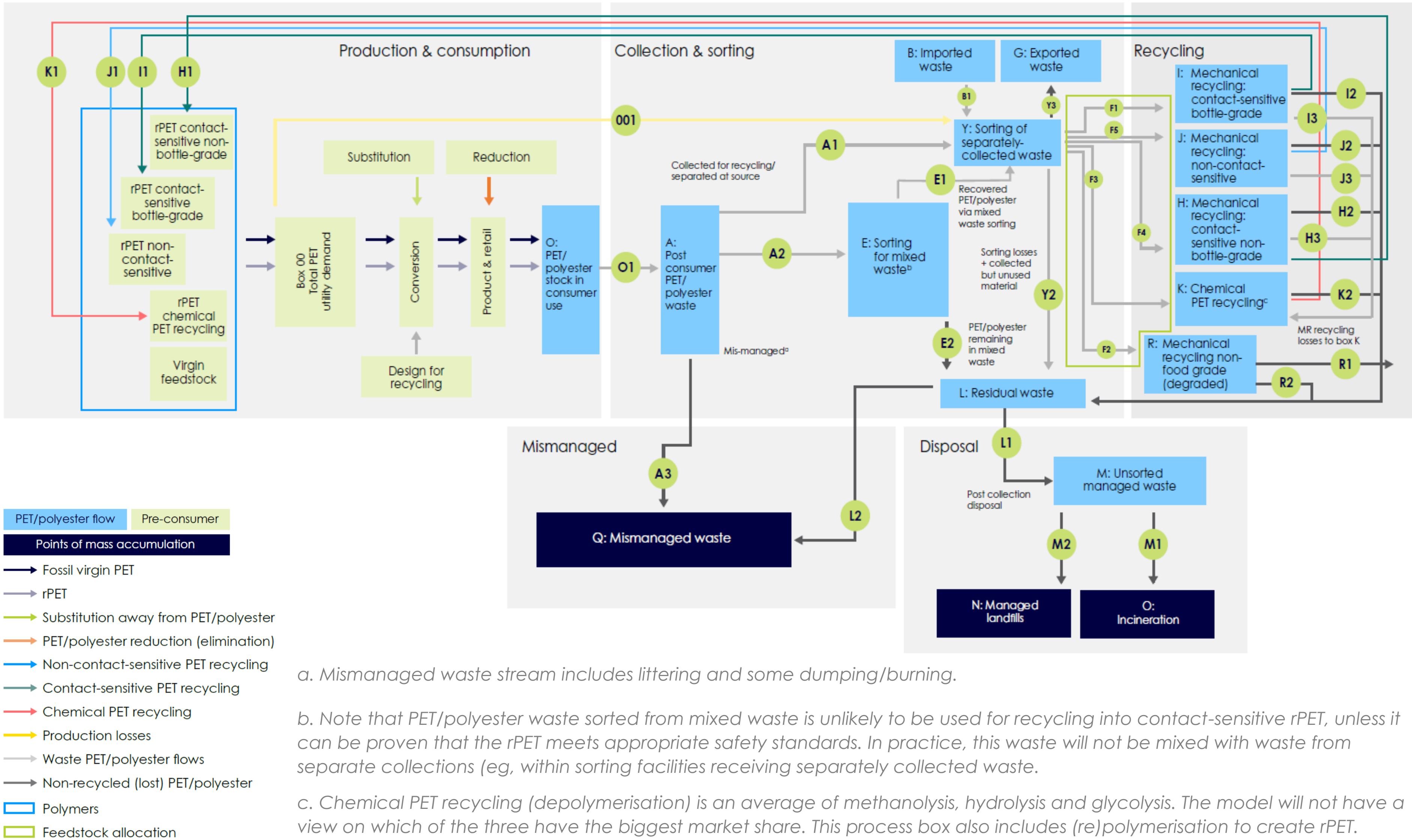
Published data and expert insights are used to set parameters for the current and potential future size of each arrow and box in the system map/model for each PET category and for each core scenario and scenario sensitivity analysis. Where data were unavailable, expert opinion was collected, or otherwise assumptions were made, the details and rationale for which are outlined in this document.

Additionally, the following metrics were mapped to the mass flows of PET: Cost in Euros per tonne of recycled PET (rPET) generated per year, GHG emissions in tonnes of CO_2 equivalent (tCO_2e) per tonne of PET passing through each system stage and jobs per tonne of PET passing through each system stage. When analyzing GHG emissions, the scope of the study covers the production and end-of-life carbon emissions only. The use-phase emissions (e.g. of washing polyester clothing) or any emissions benefits (e.g., use of downcycled polyester textiles as insulation for buildings) are not quantified within this study. Jobs associated with the export of textiles for reuse (i.e. jobs outside of Europe) are also not modelled.

The model follows an input-driven, rather than output-driven, approach. This means that system parameters, such as PET consumption per year in tonnes, waste collection rates for recycling (as a percentage of waste arising in the same year) and CO_2 emissions per tonne of material passing through each part of the system are specified. This results in downstream system outcomes being generated by the model, such as tonnes of rPET generated, rPET content percentage in new products and GHG emissions for the system. These outcomes are then evaluated against current and draft European (in this case, EU) regulatory targets. By comparison, an output-driven approach would involve defining a specific system outcome (such as a desired recycling rate for clear PET beverage bottles, or a specific percentage rPET content in new monomaterial PTTs) and then deciding on how a combination of upstream parameters should be defined in order to achieve these outcomes (of which there are a huge number of possible combinations). An input-driven approach is therefore favourable as it allows the use of e.g. historical trends and industry capabilities to set model parameters (instead of an arbitrary mix according to the achievement of a desired outcome), thus permitting stakeholders to understand the impacts of specific actions (or inaction) by specific groups on the resultant outcomes e.g. achievement of regulatory targets.

Each part of the system map is defined in the sections that follow in this document, generally listed according to the flow of mass flow within the system from left to right within the system map. In summary, the PET/polyester value chain was categorised into five major components: production and consumption; collection and sorting; recycling; disposal; and mismanagement. The boxes labelled with letters (A to Y) represent mass aggregation points in the model, and the arrows represent mass flows. Boxes outlined in bold lines represent places where PET volumes leave the system and are therefore no longer available for recycling. The boxes to the left of Box A reflect PET production and demand, by grade, as well as the places that measures to slow consumption growth act on various stages of the PET value chain. Informal collection and post-collection mismanaged waste was excluded as this is deemed irrelevant in an European context.

FIGURE 1: System map for PET/polyester packaging and textiles



a. Mismanaged waste stream includes littering and some dumping/burning.

b. Note that PET/polyester waste sorted from mixed waste is unlikely to be used for recycling into contact-sensitive rPET, unless it can be proven that the rPET meets appropriate safety standards. In practice, this waste will not be mixed with waste from separate collections (eg, within sorting facilities receiving separately collected waste.

c. Chemical PET recycling (depolymerisation) is an average of methanolysis, hydrolysis and glycolysis. The model will not have a view on which of the three have the biggest market share. This process box also includes (re)polymerisation to create rPET.

2. Modelling principles, scenario and sensitivities overview

Modelling approaches and principles

FIGURE 2: Modelling Approaches and Principles

Research question: To what extent can complementary application of interventions across the entire PET/polyester value chain, including both mechanical and chemical PET recycling, contribute towards a circular, lower CO_2 emissions economy from 2020 to 2040?

- Future scenarios are developed to **2040** and will show interim system metrics for **2030**
- We model a baseline **Historical Trends Scenario** which assumes that system developments follow historic trends. The Historical Trends Scenario does not follow future regulatory requirements [(a)]
- We model one key future scenario **(the Ambitious Complementarity Scenario)**, to provide insights on the ambitious application of current best-in-class system performance if scaled up to the entire EU27+UK
- The effects of measures to curb EU PET consumption through Reduction and Substitution (R&S) can be enabled/disabled in each scenario to examine the impacts these have

- **Variables are fixed as much as possible between scenarios** to make the scenarios comparable and to create clearer insights for decision-makers as to which factors drive outcomes
- **Sensitivity assessments** are applied to highlight the most important parameters and assumptions in the model

Notes: (a) The only exception to this is that in terms of the disposal of managed residual waste, all scenarios assume that the same decreasing proportion of residual waste flows to landfill between 2020 - 2040, in accordance with the Landfill Directive (2018) – see 'Residual waste and disposal assumptions' section below.

Overview of scenario and sensitivities construction

TABLE 2: Scenarios and sensitivities

	Scenario / sensitivity	Description
Core scenarios	Historical Trends scenario	Historical trends (without depolymerisation) continue
Core scenarios	Ambitious complementarity scenario	Complementary mechanical recycling and depolymerisation system with maximum plausible potential [(a)] in every element of the system, including measures to slow demand growth, design for recycling (D4R), collection rates, sortation for recycling rates and recycling yield rates
Key scenario sensitivities	Ambitious complementarity scenario without chemical PET recycling	Ambitious complementarity scenario but no chemical PET recycling (depolymerisation) takes place. System instead reliant on growth and development of mechanical recycling
Key scenario sensitivities	Ambitious complementarity scenario with limited waste collection and sortation	Ambitious Complementarity Scenario but the growth of collection and sortation is limited to those of the Historical Trends Scenario. Mechanical and chemical PET recycling scales to meet the supply of feedstock, as per the Ambitious Complementarity Scenario. However, the supply of feedstock, and therefore size of mechanical and chemical PET recycling industry, is lower than in the Ambitious Complementarity Scenario.

Notes: (a) Where the implementation of advanced technologies has been considered as a key bottleneck in achieving a 'growth state' e.g. higher mechanical recycling yield rates, the criterion for consideration has been that if the required technology is at technology readiness level 7 or above (i.e. proven in an operational environment, not a lab-scale) at-present, then it could reasonably be widespread in Europe by 2040 if deployed ambitiously.

In summary, two core scenarios are modelled, as further described below:

- **Historical Trends Scenario:** In this scenario, the model does not assume that system changes occur to achieve future legislative targets e.g. beverage bottle collection rates in 2025 and 2029 under the Single Use Plastic Directive (SUPD). This is because in many cases, current legislation is highly ambitious, its achievement is uncertain and therefore adoption of these targets may not create a realistic baseline. Instead, historical trends seen over the last 5-10 years (depending on data availability) in Europe continue through to 2040. This includes e.g. trends in PET/polyester consumption and collection for recycling. However, due to lack of data to show historical rate of change in other parts of the system and to what extent development has plateaued, including product design for recyclability, and technological improvement (waste sortation and mechanical recycling yield rates), 2020 performance is kept constant. Additionally, since there is no historic presence of chemical PET recycling (depolymerisation) capacity, no chemical PET recycling takes place 2020-2040.

- **Ambitious Complementarity Scenario:** Represents maximum plausible efficacy of all six system change levers (Figure 3), including mechanical PET recycling and chemical PET recycling (depolymerisation), each complementing the system according to their unique strengths. In terms of levels of performance achieved by the PET system by 2040, the key principles guiding the system parameters/assumptions are applied as below:
    - Where European legislative targets are in-place (e.g. bottle collection rates of 77% by 2025 and 90% by 2029 under the SUPD), these will be used and then further increased to reach the level of the current (2020) best-in-class collection rate across Europe by 2040.
    - Where no legislative targets are in-place, best-in-class performance (e.g. collection for recycling rates for textiles, mechanical recycling yield rates for bottles) rates will increase linearly from current levels in 2020, reaching the level of the current (2020) best-in-class collection rate across Europe by 2040.

An additional two sensitivity analyses were conducted to understand to what extent the model outcomes in the Ambitious Complementarity scenario were sensitive to the key system change levers and underlying assumptions made. These sensitivities include: (1) Ambitious complementarity scenario without chemical PET recycling and (2) Ambitious complementarity scenario with limited waste collection and sortation and are described in Table 2. Sensitivities to factors outside of those modelled in the Ambitious Complementarity Scenario were not modelled.

Note that measures to slow demand growth are applied only to the Ambitious Complementarity Scenario and the sensitivities on this scenario, whilst the European electricity grid is assumed to decarbonise in the same way across all scenarios.

A high-level overview of the system change levers enabled across each scenario is shown below:

FIGURE 3: System change levers considered

● Reduce ● Substitute ● Recycle

✓ Modelled at the level of historic trends ✓ Maximum foreseeable level

	System Interventions	Historic trends scenario[10]	Ambitious Complementarity Scenario
A	Elimination of PET and switch to reusables	✓	✓
B	Substitute PET for better alternatives	✓	✓
C	Design for recyclability	✓	✓
D	Expand collection for recycling and sortation	✓	✓
E	Mechanical recycling scale-up & improvement	✓	✓
F	Chemical PET recycling scale-up & improvement		✓

The system change levers described in the Figure 3 are:

A. **Elimination of PET and switch to reusables:** Includes eliminating PET/polyester (e.g. product redesign, reduced overpackaging, reduced production waste through better manufacturing), new product delivery models (e.g. reuse, refill services and dispensers) and consumer behaviour shifts (e.g. switch to refill water bottles at home).
B. **Substitute PET for better alternatives:** Switching to alternative materials which are suitable for incumbent PET applications, both from a functional standpoint, but are also advantageous when considering environmental impacts across their full lifecycle.
C. **Design for recyclability:** Includes shifts to clear and monomaterial formats for packaging, higher polyester purity textiles and other measures that facilitate more effective sortation and recycling.
D. **Improve and expand collection and sortation for recycling:** The scale-up of separate waste collection systems, such as for textiles and systems to sort collected PET from any non-PET it is collected alongside. Improved recovery from mixed waste is modelled also, but is understood to be much more challenging.
E. **Improve and expand mechanical recycling:** Further yield rate improvements and expansion of feedstock such as pots, tubs and trays. Scale up of capacity to keep pace with feedstock supply.
F. **Improve and expand chemical PET recycling (depolymerisation):** This technology is able to recycle some PET/ polyester applications which mechanical recycling

cannot, whilst also elevating PET waste to virgin-like quality, in cases where it has deteriorated through successive mechanical recycling loops and product applications. Significant build out needed of new plants across Europe. Continue to widen feedstock acceptance criteria and improve PET-to-PET yield.

A more detailed view about which system change levers and other high-level assumptions were enabled across each scenario or scenario sensitivity is shown in the figure below, whilst specific datapoints and references used are provided in the later sections of this document:

TABLE 3: Detailed System Change levers considered for each scenario and sensitivity

■ Described change occurs/ current best-in-class performance is European average by 2040

	Scenario / sensitivity	Design for recycling fully implem-ented [(a)]	Collected for recycling rate increased	Sorted for recycling rate increased	Mechanical recycling			Depolymerisation			
					Technology improvements		Capacit y unconst-rained	Technology improvements			Capacity unconst-rained
					Yield increased	Dedicated PTT lines producing FG and non-FG rPET		Yield increased	Multi-material trays accepted	>80% polyester accepted	
Core scenarios	Historical Trends					Limited capacity					No capacity
Core scenarios	Ambitious complementarity scenario	■	■	■	■	■	■	■	■	■	■
Key scenario sensitivities	Ambitious complementarity scenario without chemical PET recycling	■	■	■	■	■	■				No capacity
Key scenario sensitivities	Ambitious complementarity scenario with limited waste collection and sortation				■	■	■	■	■	■	■

Notes: (a) Includes switch from coloured to clear beverage bottles, from opaque to clear bottles, from multi-material to mono-material trays, from polyester blends to >80% polyester and improvement in product design for recycling

Technology Readiness Level (TRL) as a filter for system assumptions in future system

TRL is a method used to assess the maturity of a technology, which definition has been adopted by European Union using nine levels.[3] These are used to filter technologies that could be considered to be relevant and widespread to the European PET sector under the Ambitious Complementarity scenario in 2040. Typically technology below TRL 7 are not considered in this modelling exercise but additional information on technologies included vs excluded and justifications is given in the later sections of this document.

[3] Source: Definition retrieved from Science Direct article; Technology Readiness Level, https://www.sciencedirect.com/topics/engineering/technology-readiness-level, retrieved 4th May 2023

3. Model assumptions by stage of the PET system value chain and scenario

The following sections provide detailed assumptions, justification and sources for each stage of the European PET value chain across the key product categories modelled, for both the Historical Trends and Ambitious Complementarity scenarios.

European PET Consumption in 2020 and projections to 2040

Starting values for PET consumption and references are shown in the figure in section 'PET product categories chosen' above. High-level assumptions about consumption and factors relevant to consumption are given in Figure 4.

FIGURE 4: High level assumptions and factors relevant to consumption

Area	Assumptions (all scenarios)
PET consumption	• Starting values in 2020 are sourced from the literature [a]. • Given the extended time horizon and uncertainty, the historic compound annual growth rate in consumption for each product category [b] has been linearly decreased between 2020 – 2040, so that there is zero annual growth by 2040 (see next slide).
Pre-consumer losses	• Pre-consumer losses, such as production losses in the case of bottles or overstocking for textiles have not been modelled separately [c].
Design for recycling (D4R)	• D4R, where this is applied, is modelled as a shift in demand between product categories [d] (i.e. coloured bottles moving to clear and multimaterial trays switching to monomaterial trays).
Demand reduction	• The effects of a potential reduction in PET consumption (i.e. demand) due to elimination, reuse, new delivery models or substitution of PET with other materials instead are considered and applied as layers on top of existing scenarios.
Substitution into PET	• A switch from using other materials towards using PET for the same product categories used in this study, or other product types, has not been modelled [e].

Notes: (a) Refer to Table 1 for product categories and 2020 volumes and sources.

(b) Refer to Figure 5 for more information.

(c) In the case of bottles and pots, tubs and trays, production losses are understood to be in the range of 2-8% (Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate) (PET) Packaging Management Strategies in the EU, Andreasi Bassi, S., et.al (2022)), in the case of textiles, losses are known to occur at multiple pre-consumer stages (fibre, yarn and garment production, as well as losses at retailers due to overproduction). However, it is assumed that most polyester products imported into Europe are manufactured outside of Europe (e.g., in China) and therefore only retail losses are relevant. Additionally, since polyester estimates currently used are thought to represent put-on-market figures, they should also include retail losses. However, data here is poor so this assumption may be revised.

(d) The exception is textiles, where the composition of the single product category is adjusted, i.e. by 2040 50% of textiles with <80% polyester purity shift to >80% purity.

(e) Environmentally-beneficial substitution from other polymers into PET could occur if, for example, PET is considered to be easier to recycle than other polymers. Given the relatively strong annual growth rates, this substitution could be considered to be built into the existing projections.

To project the future consumption, historical compound annual growth rates (CAGRs) for the individual product categories were first sourced from the available literature (Figure 5). Through discussion with the project's expert Steering Committee and since Europe's population is expected to contract slightly over the next 20 years, a continuation of historic growth rates for entire 20-year period was not considered to be justifiable. Instead, the historic CAGRs were linearly decreased until there was no further consumption growth in 2040 (i.e. CAGRs equal to zero, Figure 5). This still results in a 44% growth in the mass of PET consumed between 2020 and 2040, reaching slightly more than 11Mt by 2040.

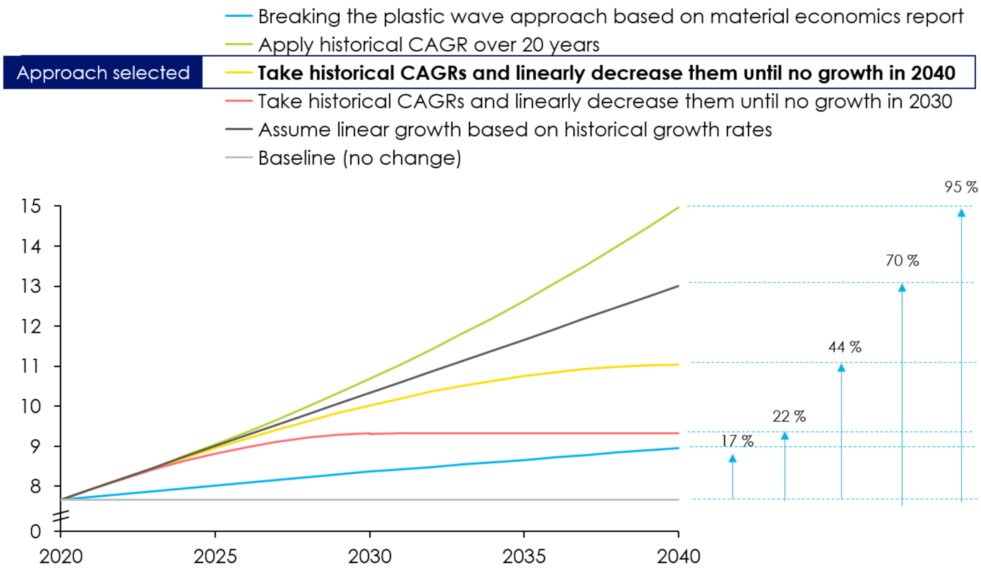
FIGURE 5: PET consumption growth under different scenario

Historical growth rates [1]

Product category	CAGR
Clear bottles	2.4%
Mixed bottles	2.4 %
Trays	5.4%
PET strapping	4 %
PET film	3.4 %
Textiles	4.0 %

Population EU27 + UK [2]

Year	Population EU+ UK
2020	515.0 Million
2030	516.5 Million
2040	514.1 Million



Sources: (1) Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate) (PET) Packaging Management Strategies in the EU, Andreasi Bassi, S., et.al (2022), (2) Eurostat

Note: PET demand increase over time implicitly accounts for substitution into PET, e.g. from single use glass / HDPE/ PP rigids etc

Effects of circular economy measures to slow PET consumption growth (reduction, substitution and reuse)

To model measures that could slow the trend in increasing PET consumption (e.g. through system interventions), three mutually-exclusive levers were considered and applied to annual product category consumption, as relevant: elimination, reuse and substitution (Figure 6). These levers were applied simultaneously, i.e. the percentage reduction in the weight of annual consumption as a result of each lever is calculated independently, then these reductions are subtracted altogether from the starting annual consumption to get the final annual consumption. Note the below definitions are packaging-centric, whereas for textiles, the summary table of the percentage impacts of these measures gives relevant examples.

FIGURE 6: System interventions to slow PET packaging consumption growth

Lever	Definition	Examples
Eliminate	▪ Policy interventions, innovations and consumer behavior shifts which lead to reduced plastic material demand for low-utility plastic, that **does not require a replacement**	▪ Reduce over-packaging, develop packaging-free products, ban unnecessary plastics, increase utility per package ▪ Extended lifetime
Re-use / New delivery models (NDM)	▪ Replacement of single-use products and packages with re-usable items **owned and managed by the user**	▪ Reusables owned by consumers (e.g. water bottles)
	▪ **Services and businesses which provide the utility** previously furnished by single-use plastics, with reduced material demand	▪ Refill from dispensers, subscription services, concentrated product capsules, take-back services with reverse logistics and washing (e.g. SodaStream) ▪ Package-as-a-service models (e.g. packaging-free deliveries)
Substitute	▪ **Substitution of single used plastic by non-plastic alternative**	▪ Substitution with paper / coated paper

To determine the demand reduction values for the individual levers per product category, the following approach heiriarchy was taken:

1. **Use existing draft/final regulatory requirements if applicable to our categories (e.g. draft PPWR).**

If approach #1 is not applicable:

2. **Use Systemiq approach developed for the Reshaping Plastics report (2022), based on 'Maximum Market Penetration Potential' of specific lever, if applicable to the selected PET product categories.**

If approach #2 is not applicable:

3. **Use external source (e.g. expert interviews) to evaluate the potential of any given lever to slow consumption growth.**

A summary of the reductions in demand (as a percentage of annual demand) in both 2030 and 2040 for each product category and for each lever is given below, as well as a brief description of the information and sources relied upon. The following sections provide more detail, where necessary, on the basis for these numbers. For textiles, the relevant information is provided in Figure 7.

FIGURE 7: Product category assumptions for elimination, reuse and substitution

	Elimination potential			Reuse / NDM [d] potential			Substitution potential [e]		
Product category	2030	2040	Comments	2030	2040	Comments	2030	2040	Comments
Clear beverage bottles	1%	10%	Reshaping Plastic Method: Elimination because of refill at home	9%	22%	PPWR Reuse targets (10, 25 %), 88% Mass reduction ratio [a]	0%	0%	
Colored beverage bottles	0%	0%		9%	22%	PPWR Reuse targets (10, 25 %), 88% Mass reduction ratio [a]	0%	0%	
Non-food and beverage bottles	1%	10%	Reshaping Plastic Method: EMF Upstream innovation - Solid products instead of liquid, e.g. soaps etc., dissolvable packaging	9%	22%	Use PPWR Reuse targets for FG bottles (10, 25 %), 88% Mass reduction ratio [a]	0%	0%	
Pots, tubs and trays	6%[b]	14%	Reshaping Plastic Method: Packaging-free fresh produce aisles, shorten supply chains, enhance life using coatings directly on produce, not individual packaging	5 %	13%	Reshaping Plastic Method: Home delivery services, farmers' markets, returnable packages; Refill dispensers and returnable packaging EG LOOP	12%	20%	Reshaping Plastic Method: Substitution with paper and coated paper [c]
Other packaging (Strapping is 30% of this category)	-	-		3%	8 %	PPWR Reuse targets (10, 30 %), 88% Mass reduction ratio [a], applied to strapping only (30% of category)	-	-	
Textiles	8%	15%	Includes 5% reduction due to wastage reduction along the manufacturing value chain (PET to fiber, fiber to garment and garment to finished product) as well as 10% reduction due to less overproduction and seasonal collections and more multifunctional garments instead McKinsey, Fashion on Climate, 2020; McKinsey, Scaling Textile Recycling in Europe (2022) Expert interviews	10%	20%	Includes consumer and business shifts to reuse via rental models, recommerce, repair and upcycling. McKinsey, Fashion on Climate, 2020; McKinsey, Scaling Textile Recycling in Europe (2022), Expert interviews	3 %	5 %	Include substitution to new fibers (e.g., man made natural fibers) McKinsey, Fashion on Climate, 2020; McKinsey, Scaling Textile Recycling in Europe (2022), Expert interviews

Notes: (a) Determination by Case study (Breaking the Plastic Wave, Systemiq (2020)). 22% final reduction in consumption due to reuse in 2040 is calculated as 25% reuse target x 88% mass reduction ratio (as some PET mass remains when switch to reusable versions of the bottles)

(b) Example Calculation: 20% (market penetration potential sub-category) x 28% (size of product sub-category)

(c) "Single-use plastic take-away food packaging and its alternatives", United Nations environment program 2020, page 24;

(d) NDM = New Delivery Model

(e) Substitution does not take into account a switch to compostable plastics

1. Use regulatory requirements if applicable to our categories

The draft of the Plastic Packaging Waste Regulation (PPWR[4]) was identified as relevant to two key PET product categories: PET beverage bottles and industrial strapping. The 2030 and 2040 targets are shown in Figure 8.

[4] Plastic Packaging Waste Regulation, Draft published in Nov 2022, EU Commission

FIGURE 8: Reuse targets from plastic packaging waste regulation draft

Description: Targets proposed for selected sectors with the greatest potential for reuse
To be met by economic operators

Legal targets

Category	2030	2040
Take-away cold and hot beverages	20%	80%
Take-away ready prepared food	10%	40%
Alcoholic beverages other than wine or spirits	10%	25%
Wine	5%	15%
Non-alcoholic beverages	10%	25%
Transport packaging (e.g., pallets, drums)	30%	90%

Category	2030	2040
Transport packaging shipped domestically	100%	100%
Transport packaging via e-commerce	10%	50%
Transport packaging accessories (incl. strapping)	10%	30%
Grouped packaging	10%	25%
Transport for household appliances	90%	90%

Note that these reuse percentages are not applied directly as reductions in PET demand. Instead they are attentuated by the mass reduction ratio i.e. a switch to a reusable alternative of the same product, made of a more robust version of the same material (e.g. to thicker, reusable PET bottles) This means that there will still be some PET demand for these reusable alternatives once a switch to reusables has taken place.

More information on the assumed mass reduction ratio is given below.

2. Use Systemiq approach developed for the Reshaping Plastics report (2022), based on 'Maximum Market Penetration Potential' of specific lever, if applicable to the selected PET product categories

Measures to slow consumption growth have been individually scored to assess their potential market penetration using a 5-test framework developed by Systemiq during the development of the Reshaping Plastics report. This is shown in Figure 9.

FIGURE 9: Elimination, reuse and substitution scoring matrix

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
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 business as usual	Green	50%	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%
Only in labs: TRL 1-4	Partially: limited applications only	Partially: externalities small increase of environmental compared to alternative	Partially: eco-conscious consumers only	Partially: eco-conscious consumer only	Orange	1%	10%
No alternative available	Unacceptable health or performance risk	Unacceptable increase in environmental externalities	Unacceptable cost increase	Unacceptable lifestyle change	Red	0%	0%

Note: The penetration rate potential in the orange category is capped for the "Elimination" lever at 10% in 2040, except in the case of PTTs.

An overview of how this framework has been applied to the PET packaging categories modelled is shown below. Note that (1) the product subcategory breakdown is an estimate as it relates to food-related pots, tubs and trays of all polymer types, rather than PET specifically as no PET-specific market data was available. (2) Elimination, reuse and substitution are applied simultaneously. (2) For PTTs, a weighted average is taken for all subcategories. (3) Mass reduction ratio New delivery model (NDM)/Reuse: 88 % (Figure 11). (4) Reduction potential of PTTs generally (all materials) is used as a proxy for PET PTTs.

FIGURE 10: Elimination, reuse and substitution scoring results for each packaging category

Product application	Product sub-category	% of product application	Eliminate	Re-use	New Delivery Model	Substitution to paper	Substitution to coated paper
Clear beverage bottles			Orange	PPWR target used		N/a	N/a
Coloured beverage bottles			N/a	PPWR target used		N/a	N/a
Non-food-and-beverage bottles			Orange	PPWR target used		N/a	N/a
Other Packaging	Strapping only	30%	N/a	PPWR target used		N/a	N/a
Pots tubs and trays	Fresh fruit/vegetables tray/pot/punnet/tub	28%	Yellow	Orange	Yellow	Green	N/a
	Pots/tubs for liquids and creams: Yoghurt, butter, spreads, chocolate/sweets, cream, chilled pot desserts & ice cream pots/tubs	24%	Red	N/a	Orange	N/a	Orange
	Meat tray	12%	Red	Orange	N/a	N/a	Orange
	Ready meals trays, instant pot snacks	8%	Red	N/a	Orange	Yellow	Orange
	Other	28%	Red	N/a	N/a	N/a	Orange

An overview of the case studies used to inform the expected mass reduction ratio for PET products subject to reductions in consumption as a result of reuse are shown in Figure 11.

FIGURE 11: Mass reduction ratio for reuse

Case studies for the identification of mass reduction ratio for Reuse / NDM

Case study	Method and assumptions	Waste Ratio
Replenish (*205*)	Published waste reduction figure of 90%.	10%
Algramo*	Based on 75% reduction in bottles required.	25%
Cupclub	Re-usable cup and lid weighing 71.33g (=49.3+22.03g), reused 132 times, compared to a single-use expanded polystyrene (EPS) cup weighing 6.4g (=3.2+3.2g).	8%
Swedish Return System	Based on reusing a crate 150 times weighing 1.63kg (*206*), compared to a single-use crate weighing 60% less (*207*).	2%
Refill bottle scheme†	Based on 16 reuses of a 91g 2L returnable bottle, compared to a single-use 2L PET bottle weighing 41g	14%

*Confidential sales data analysis provided by Algramo on the company's sales of refill products (June-Sept 2018).
†Confidential data provided by expert interview with a brand running both refill and non-refill bottle schemes.

Average waste ratio of 12 %, corresponding to an average mass reduction ratio of 88 %.

Source: Breaking the Plastic Wave, Systemiq (2020)

New product categories have not been created to capture the reusable alternatives of existing PET products, which are assumed also made from PET due to their relatively small market share. However, it is acknowledged that the lifetimes of these products, their collection and recycling pathways may differ from their non-reusable counterparts.

Design for recycling (D4R)

Design for recycling/recyclability (D4R) are changes in product design made by manufacturers/ PET converters in order to facilitate more effective recycling at end of life of the products. These changes could enable both easier sortation of target PET products from other non-PET products at waste sortation facilities (also known as Material Recovery Facilities; MRFs) and during additional pre-sortation at recyclers. Ultimately it results in higher yield rates from sorting, pre-treatments, as well as recycling - both mechanical and chemical.

In the model, for PET packaging, D4R works by shifting a certain percentage of the annual consumption of product types which are considered to be harder to recycle (e.g. coloured beverage bottles, multimaterial PTTs) to similar existing product categories considered to be easier to recycle (e.g. clear beverage bottles, monomaterial PTTs). A 90% shift from harder to recycle product types towards more recyclable counterparts is modelled by 2040. In the years 2020-2040, this percentage shift increases linearly from 0-90%. The feasibility of this assumption was validated with a number of PET brands, recyclers and other subject matter experts in Europe.

For textiles, first, the polyester purity distribution of the product category as of 2020 has been determined from external sources (Figure 26). Generally speaking , this is divided into three categories: 100% polyester purity, 80-99% polyester purity and below 80% polyester purity polyester textiles. A 50% shift in the consumption of <80% polyester purity to 80-99% polyester purity textiles is assumed to take place by 2040 and this level is achieved through a linear increase from 0% to 50% between 2020 – 2040 (Figure 12).

The final mix of PET products consumed in any given year, in scenarios where D4R is taking place is the result of the above shifts.

FIGURE 12: Design for recycling assumptions

D4R lever	Assumptions
Shift from coloured food and beverage bottles to clear bottles	90% shift by 2040 (linear increase)[b]
Shift from opaque food and beverage bottles to clear bottles	90% shift by 2040 (linear increase)[b]
Shift from multimaterial PTTs to mono-material PTTs	90% shift by 2040 (linear increase)[b]
Shift from lower polyester content textile blends to higher content blends	50% of polyester textiles placed on the market with less than 80% polyester shift to having 80-99% polyester content by 2040 (linear increase)[c]

Note: (a) The proportions of products put on the European market remain as they were in 2020 i.e. the proportions of coloured, clear and non-beverage bottles, as well as the proportions of clear monomaterial vs clear multimaterial pots, tubs and trays (PTTs) and polyester purity all remain fixed whilst consumption rates increase.

(b) This percentage shift is based upon expert input by European PET packaging brands, recyclers and other experts. Additionally, higher producer fees for packaging that is considered to be less recyclable are envisaged by the draft PPWR. This may place downward pressure on types of packaging (e.g. multimaterial PTTs, coloured bottles) which are harder to recycle and/or produce lower-grade rPET output, therefore disincentivizing the placement of these products on the market and instead incentivizing a switch to e.g. monomaterial/clear alternatives. However, the exact design for recyclability criteria and methodology for assessment are expected to be clarified in future delegated acts.

(c) Although not currently mandatory, under the Ecodesign for Sustainable Products Regulation, the European Commission intends to "develop binding product specific ecodesign requirements to increase textiles' performance in terms of durability, reusability, reparability, fibre-to-fibre recyclability and mandatory recycled fibre content". Recycled content targets will be easier to achieve if textiles are first easier to recycle (thus ensuring higher availability of secondary materials) and fibre blends are specifically mentioned as one obstacle to improving recyclability. This may encourage a shift towards polyester blends with a higher polyester content.#

PET waste production and waste collection

Following consumption of PET products, this PET eventually ends up arising as waste in Europe. For packaging, waste production is assumed to take place in the same year (therefore e.g. production and consumption in 2030 = waste creation in 2030)[5]. For textiles, products are assumed to have a 5-year lifetime on-average[5]. This means that for textiles consumed in year x, the probability of these products becoming waste follows a normal distribution curve with a peak at x+5 years and a shape variable of 2.5. The amount of this waste arising in any given year is therefore calculated using an appropriate Weibull distribution table within the model. Because of the presence of textile, waste production lags behind consumption.

This waste can then follow one of three pathways within the model, given as arrows A1, A2 and A3 (Figure 13).

FIGURE 13: System map focus on waste generation pathways

Notes: (a) In the case of bottles and PTTs, production losses are understood to be in the range of 2-8% (Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate) (PET) Packaging Management Strategies in the EU, Andreasi Bassi, S., et.al (2022)) but due to lack of data on where these losses occur and flow to, they have not been modelled at-present. In the case of textiles, losses are known to occur at multiple pre-consumer stages (fibre, yarn and garment production, as well as losses at retailers due to overproduction). However, it is assumed that most polyester products imported into Europe are manufactured outside of Europe (e.g. in China) and therefore only retail losses are relevant. Additionally, since polyester estimates currently used are thought to represent put-on-market figures, they should also include retail losses. However, data here is poor so this is an area where more data is needed.

(b) Each PET packaging category is assumed to have a flat mismanagement rate of 2% of the amount of waste created. This rate is sourced from expert panel input gathered during creation of Systemiq's ReShaping Plastics (2022) report. A lower rate of 0.5% has been used for textiles as leakage is assumed to be less likely.

(c) Deposit Return Scheme

Arrow A1: Collected for Recycling/Separated at source: first, the proportion of separately-collected waste as a percentage of all waste arising that year is calculated (arrow A1). This includes all modes of separate collection e.g. deposit return schemes (DRS) using e.g. reverse vending machines, home / kerbside waste collections, bring banks, and in the case of textiles includes donations to key donation points (textiles on-street drop-off banks, charity

[5] Roland Geyer et al. ,Production, use, and fate of all plastics ever made, Sci. Adv. (2017)

shops etc). The general approach to how the amount of separately-collected PET waste was projected and calculated for each PET product category and each core scenario is shown in Figure 14, 15 and 16.

Arrow A3: Mismanaged Waste: The percentage of all waste arising that is mismanaged is then calculated (Figure 13). Each PET packaging category is assumed to have a flat mismanagement rate of 2% of the amount of waste created. A lower rate of 0.5% has been used for textiles as leakage is assumed to be less likely. This percentage is constant across all scenarios therefore its magnitude (in tonnes) varies with the total amount of waste created.

Arrow A2: Collection of mixed waste: After these values have been calculated, any remaining waste arising is assumed to be collected as mixed waste (arrow A2).

Arrow 001: Pre-consumer waste: As noted previously, although the model has the capability to track the flow of pre-consumer PET waste travelling directly from manufacturers, retailers etc to waste facilities, no reliable data was available on these flows of material and therefore any pre-consumer waste flows taking place were assumed to be included in the major flows of each PET product category through the system.

FIGURE 14: Collection – collected for recycling (arrow A1) assumptions overview and approach

Scenario/system state	Assumptions
Historic Trends	• Linear increase using historic collection rates to 2040, where data is available • Where there is a lack of historic collections data, the historic rate of the most similar PET product will be used • Where no collections are taking place, or collection rates are very approximate (e.g. 'other' packaging), the 2020 rate is assumed to stay constant
Growth scenarios	• Where European legislative targets are in-place [(b)], these will be used and then further increased to 2040 reaching the level of the best-in-class collection rate (2020) • Where no targets are in-place, collection rates will increase linearly to 2040, reaching the level of the best-in-class collection rate (2020)

Note: (a) In the case of PET packaging (bottles, PTTs etc), the weight of waste arising is the same as that placed on the market in the same calendar year. For textiles, waste arising takes into account an average lag time of 5 years for products put on the market to become waste.

(b) For example, SUPD PET beverage bottle collection rates of 90% of the bottles place on the market by 2029.

FIGURE 15: Historical trends scenario: collected for recycling (A1) assumptions

Product category collected	Collection rate (2020)	Historic European collection rate increase	Projected collection rate by 2040	Comments
Clear food and beverage bottles	72% (1) (3) (a)	0.6% (2)	**84%**	Between 2013-2018, 'sent for recycling' rates of European PET bottles rose from 49% to 52% (2) (0.6% per year (c)). This growth rate has been assumed to represent the rise in collection rates over the same period and is then projected forwards between 2020-2040 for all PET bottles.
Coloured food and beverage bottles	71% (1) (3) (a)		**83%**	
Non-food and beverage bottles	70% (1) (3) (a)		**82%**	
Mono-material pots, tubs, trays (PTTs)	29% (2)(3) (a)	n/a	**41%**	Due to lack of available data, the historic increase in bottle 'sent for recycling' has also been applied to trays (c).
Multi-material PTTs	20%(2)(3) (a)		**32%**	
Other packaging (i.e. strapping, film)	~0%	n/a	**0%**	This assumes collection rates remain insignificant due to lack of targeted collections for these products.
Textiles	38% (5) (b)	n/a	**58% (d)**	Many European countries have setup collection systems for textiles but given the lack of historic European collection rate data, the collection rate is assumed to increase at a low rate (1% per year).

Sources: (1) How circular is PET?, Eunomia and Zero Waste Europe (2022), (2) PET Market: State of Play 2022, Eunomia (2022), (3) Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate)(PET) Packaging Management Strategies in the EU,- Supporting Information A, A.Bassi et.al (2022), (4) Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers, I. Antonopoulos et.al. (2021), (5) Circular economy perspectives in the EU Textile sector, JRC (2021)

Notes: (a) No European collection rate data was available, only data on the weight of bales sorted for recycling from (1) and (2). Collection rates have therefore been back-calculated using average Material Recovery Facility (MRF) sortation yield rates from (3) and (4). For more details on sortation rates for clean waste, see the later sections 'Historic trends: Sorting for clean waste (Box Y) – assumptions'.

(b) For textiles, this is the total separately collected textiles rate (for household apparel and textiles), for both reuse and recycling.

(c) This rate is likely to factor in collection rate increases due to the adoption of DRS by various countries across Europe in recent years, which generally raises collection rates significantly over a short timespan, and therefore may be too optimistic (especially for PTTs). The projected growth rate is therefore likely to factor in some further adoption of DRS in the case of bottles.

(d) The Waste Framework Directive (2018) establishes that EU member states must setup separate collections for textiles by 2025, however the directive sets no collection targets. JRC research predicts a 3-4% annual increase in the years leading up to 2025, though here we have taken a more conservative 1% annual rate increase between 2020 – 2040 to account for uncertainty and a longer timeframe.

FIGURE 16: Ambitious complementarity scenario (and relevant sensitivities): collected for recycling (A1) assumptions

Product category collected	Collection rate [(a)] (2020)	Legislative collection Target	Best in-class collection rate identified	2040 collection rate	Comments
Clear food and beverage bottles	72% [(1) (3)]	77% by 2025 90% by 2029 [(5)]	96% [(2)]	**96%**	Between 2030-2040, the collection rate increases from the legislative target to the Danish PET bottle collection rate achieved via DRS in 2020
Coloured food and beverage bottles	71% [(1) (3)]	77% by 2025 90% by 2029 [(5)]	96% [(2)]	**96%**	
Non-food and beverage bottles	70% [(1) (3)]	n/a	92% [(2)]	**92%**	A linear increase is assumed between 2020-2040 to the level of the best in-class PET bottle collection rate for a country without a DRS (Belgium) in 2020
Mono-material pots, tubs, trays (PTTs)	29% [(2) (3)]	n/a	None identified	**92%**	Given the low best-in-class rate, a linear increase is chosen, up to the Belgian collection rate for a similar packaging product collected without DRS: PET bottles
Multi-material PTTs	20% [(2) (3)]				
Other packaging (i.e. strapping, film)	~0%	n/a	None identified	**15%**	This assumes targeted, wide-spread collections for strapping (but not PET film) are put in place by 2040, reaching 50% of strapping placed on the market [(b)]
Textiles	38% [(4)]	n/a	75% [(6)]	**75%**	A linear increase is assumed, up to the German 2013 collection rate for clothing and footwear

Sources: (1) How circular is PET?, Eunomia and Zero Waste Europe (2022), (2) PET Market: State of Play 2022, Eunomia (2022), (3) Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate)(PET) Packaging Management Strategies in the EU,- Supporting Information A, A.Bassi et.al (2022), (4) Circular economy perspectives in the EU Textile sector, JRC (2021), (5) Single Use Plastic Directive (SUPD): Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment,(6) Used Textile Collection in European Cities, Watson et al (2018) - Study commissioned by Rijkswaterstaat under the European Clothing Action Plan (ECAP)

(a) This is the total collection rate for recycling (and reuse, in the case of textiles).

(b) Assumption based upon best estimates, no specific data available. The assumption is that by 2040, 50% of strapping will be collected, which makes up ~30% of consumption for Other PET packaging, giving an overall weighted average collection rate for this category of 15%, when considering PET film too.

Sortation of collected waste for recycling

Once waste is collected, either through separate collections or through mixed waste collections, it generally needs to undergo sortation to segregate target materials (here PET) from non-PET recyclate or contamination.

Box E: Mixed waste sortation: Due to the much higher heterogeneity in types of items arising in mixed waste collections, including potentially high contamination with food, fluids and other substances, successful sortation of PET from this waste is assumed to be very challenging and generally low-yield. Where this does take place, it is modelled as the flow of products via Arrow A2 to Box E in the system map, with successfully-sorted products being passed via arrow E1 to clean waste sorting facilities (box Y) for further sortation, and remaining unsorted PET waste being sent via arrow E2 to box L (residual waste). Note that PET waste arriving to Box E via Arrow A2 is what remains after separate collections and mismanagement. For e.g. beverage bottles which are assumed to have very high separate collection rates in 2040 (~90-95%), the amount of PET waste remaining in mixed waste is therefore very low.

The general approach to how PET waste sortation was projected and calculated for each PET product category, each core scenario and for mixed waste collections is shown in the figures 17, 18 and 19.

Box Y: sortation of clean, separately-collected waste: Most sortation that results in the creation of (relatively) clean, sorted and homogenous feedstocks for recycling (and reuse, in the case of textiles) takes place at MRFs (for packaging) and textiles sortation facilities (in the case of textiles) which are receiving separately-collected PET/polyester waste. Textiles sortation facilities are generally very manually-intensive operations whereas MRFs can be highly-automated. Box Y has several potential inputs and outputs:

- Inputs: aside from the main input of separately-collected clean PET waste (Arrow A1), and the secondary input of sorted PET waste arriving from box E, imports of waste is also included. However, imports at this stage have been considered negligible and no imports for processing and recycling are modelled.
- Outputs: The main output of Box Y is sorted PET waste used as feedstock for recycling, which is allocated across arrows F1 – F5 (refer to the section on feedstock allocation). The model also has the capability to export waste outside of Europe, though this only takes place for the export of reusable textiles for markets outside of Europe. For any remaining PET waste that was either not successfully sorted for recycling/reuse or exported, this travels via arrow Y2 to residual waste. This can be thought of sorting facility inefficiencies or items unsuitable for recycling e.g. due to high contamination.

As discussed above, sortation input capacity (at both Box Y and Box E) is not constrained and assumed to scale in proportion to the quantity of PET waste arriving via arrows A1 and A2. In conversation with industry experts, the build-out of this capacity has not been flagged as a risk, especially as PET tends to be one of the higher-value feedstocks sold by sortation facilities.

The general approach to how PET waste sortation was projected and calculated for each PET product category, each core scenario and for separately-collected waste collections is shown in the figures 20, 21 and 22.

Arrow B1: Imports of waste collected for recycling: As mentioned above, no imports of PET waste into Europe are assumed to take place as no evidence was obtained indicating this currently occurs.

Arrow Y3: Exports of waste collected for recycling: For the export of PET from Europe across all scenarios, assumptions are described in Figure 23.

FIGURE 17: Sorting of mixed waste (Box E) - assumptions overview and approach

Scenario/system state	Assumptions
Historic Trends	• No improvement is assumed and the sortation rate stays constant

Growth scenarios	• For each product category, sortation rates increase linearly to 2040, reaching the higher of the following values, depending on data availability:
	  • Any regulatory target for sortation rate; or
	  • the level of the best-in-class sortation rate/facility currently available on the market

Note: Sorting for mixed waste refers to sortation of PET products from mixed waste sent to residual waste processing facilities (box E in the system map), prior to remaining residual waste being sent to landfill/incineration.

FIGURE 18: Historical trends scenario: sorting of mixed waste (Box E) - Assumptions

Product category collected	Sorted for recycling yield rate (2020)	Historic European sortation yield rate increase	Projected sortation yield rate by 2040	Comments
Clear food and beverage bottles	3% (1)	n/a	**3%** (1)	Assumes limited sortation of PET packaging from mixed waste persists. Poor data, no historic trends available.
Coloured food and beverage bottles			**3%** (1)	
Non-food and beverage bottles			**3%** (1)	
Mono-material pots, tubs, trays (PTTs)	3% (1)	n/a	**3%** (1)	
Multi-material PTTs				
Other packaging (i.e. strapping, film)	0% (1)	n/a	**0%** (1)	No evidence found in the literature or through existing expert interviews that this is happening at any significant scale across Europe in 2020. This situation is assumed to persist.
Textiles	0% (1)	n/a	**0%** (1)	

Sources: (1) Expert panel input during ReShaping Plastics report, Systemiq, 2022 and discussions with European PET recyclers (2023) and trade groups

FIGURE 19: Ambitious complementarity scenario (and relevant sensitivities): Sorting of Mixed waste (Box E) - assumptions

Product category collected	Sorted for recycling yield rate (2020)	Best in-class sortation yield rate identified	2040 sortation yield rate	Comments
Clear food and beverage bottles	3% [1]	n/a	**60%**	EU legislation [2] stipulates that 65% of municipal waste created must be sorted for recycling by 2035. It is envisaged that this target is likely to be met in large part through separate collections of waste for recycling. However, given the anticipated pressure in future to source rPET to meet planned recycled content legislative targets and since many existing commercial sorting technologies could be applied to mixed waste [3], a relatively high mixed waste sortation rate is feasible. For PET bottles and PTTs, a more conservative 60% sortation rate has been applied to the sortation of mixed waste specifically, by 2040 [a]. For 'other packaging' this is applied only to the strapping portion of this waste stream, giving a final sortation rate of 11%. For textiles, due to limited anecdotal evidence of this practice being trialed, the higher potential for contamination, and the issues this is likely to present to downstream sortation and recycling facilities, a 10% maximum rate has been applied by 2040 as a best-estimate.
Coloured food and beverage bottles				
Non-food and beverage bottles				
Mono-material pots, tubs, trays (PTTs)	3% [1]	n/a	**60%**	
Multi-material PTTs				
Other packaging (i.e. strapping, film)	0% [1]	n/a	**11%**	
Textiles	0% [1]	n/a	**10%**	

Sources: (1) Expert panel input during ReShaping Plastics report, Systemiq, 2022 and discussions with European PET recyclers (2023) and trade groups, (2) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, European Commission (2008), (3) Mixed Waste Sorting to meet the EU's Circular Economy Objectives, Eunomia (2023)

Notes: (a) This is a best-estimate assumption but has a relatively low impact on the results of this study as by 2040, most scenarios envisage that the vast majority of PET packaging is being collected for recycling separately (i.e. not through mixed waste). This leaves little remaining in mixed waste to be sorted.

FIGURE 20: Sorting of clean, separately-collected waste (Box Y) - assumptions overview and approach

Sortation [a] means the ability for a waste sortation plant to successfully segregate target (PET) materials from the plant's input stream. It is mostly driven by the quality/contamination of the input material and sortation technology capability. Sortation yield rate is calculated as the weight of successfully sorted recyclate leaving sortation facilities divided by the weight of the same (collected) recyclate entering the same facilities, in the same calendar year.

Scenario/system state	Assumptions
Historic Trends	• No improvement is assumed and the sortation rate stays constant
Growth scenarios	• For each product category, sortation rates increase linearly to 2040, reaching the higher of the following values, depending on data availability: • Any regulatory target for sortation rate; or • the level of the best-in-class sortation rate/facility currently available on the market

Notes: (a) For PET packaging, the sortation rate is the average rate across the European facilities that PET packaging is being sent to, which in most cases will be Material Recovery Facilities (MRFs) receiving mixed recyclate. For textiles, this refers to European textiles sorting facilities which receive textiles and sort for reuse, recycling and downcycling. Sortation (and diversion) of textiles that were incorrectly disposed of by the public with mixed recyclates (i.e. arriving at MRFs) has not been considered.

Additionally, for PET packaging, in most cases there is no true 'collection rate' data, since most bottles and PTTs are not recorded at the point of collection (as they are often mixed with other recyclate). Therefore, sortation rates are used to back calculate the collection rate, based upon available data on the weight of PET packaging sorted for recycling.

FIGURE 21: Historical trends scenario: sorting of clean waste (Box Y) - Assumptions

Product category collected	Sorted for recycling yield rate (2020)	Historic European sortation yield rate increase	Projected sortation yield rate by 2040	Comments
Clear food and beverage bottles	84% [(1) (2) (a)]	n/a	**Unchanged**	No historic trend data available on sortation rate improvement. Assume rate stays fixed, as for recycling yields (see following sections).
Coloured food and beverage bottles				
Non-food and beverage bottles				
Mono-material pots, tubs, trays (PTTs)	20% [(2)(b)]	n/a	**Unchanged**	No historic trend data available on sortation rate improvement. Assume rate stays fixed. See additional notes [(b)].
Multi-material PTTs				
Other packaging (i.e. strapping, film)	~0%	n/a	**Unchanged**	No evidence of targeted collections or sortation
Textiles	98% [(4) (c)]	n/a	**96%** [(c)]	In 2020, ~ 68% of collected polyester textiles are exported for reuse, ~30% downcycled and ~2% sent to residual waste [(4) (c)]

Sources: (1) Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate)(PET) Packaging Management Strategies in the EU,- Supporting Information A, A.Bassi et.al (2022), (2) Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers, I. Antonopoulos et.al. (2021), (3) PET Market: State of Play 2022, Eunomia (2022), (4) Sorting for Circularity Europe, Fashion for Good (2022)

Notes: (a) The 2020 value is the average from various publications, including data from Material Recovery Facilities (MRFs) with bale output purity above 95%. No data obtained on sort rates per bottle colour. It is anticipated available sortation rates include some level of impurities and non-target materials, therefore the sortation rates for PET only may be higher. However, reliable data on this was not available to improve the rates used.

(b) The cited average European sortation rate for PTTs in 2020 in the literature (2) is 80%. However, PTT data is poor generally, and none of the data sources provide a PTT-specific sortation rate, only a rate for MRFs sorting a mix of PET bottles and PTTS, therefore confidence in this figure is low. Whilst market data suggests around 20% of PTTs put on the market are sorted for recycling (3), conversations with European recycling industry experts indicate that as of 2020, only 25% of these sorted PTTs are mechanically recycled to produce rPET flake, either when PTTs are included within PET bottle bales or where there are dedicated PTT mechanical recycling lines for sorted PTT bales e.g. by organisations such as Wellmann, Faerch and Repetco. Therefore the majority (75%) of sorted PTTs are understood to be sent to a mix of downcycling into more difficult-to-recycle applications or being sent to landfill/incineration. Due to uncertainty around the breakdown of end-destinations for this 75% of sorted PTTs, they have all been assumed to be sent to residual waste at the sortation stage, meaning that the effective sorted for recycling rate is 20% on average.

(c) Sortation at textiles sorters refers to the rate at which collected textiles arriving at sortation plants are sorted for reuse, recycling and downcycling, as compared to being rejected and sent to residual waste(landfill/incineration). Additionally, as with packaging, the rates cited only refer to PET material coming into sorting facilities (and not e.g. contamination with non-PET items). However polyester blends are included, but not the weight of the non-polyester materials within them. As low-grade textiles can find various downcycled applications, sortation/yield rates even in 2020 are considered to be very high, according to Systemiq analysis of polyester textile flows data from (4) and discussions with the author of this report. Sort rates are expected to decrease as collection rates increase and the share of non-reusable textiles increases.

FIGURE 22: Ambitious complementarity scenario (and relevant sensitivities): Sorting of clean waste (Box Y) - assumptions

Product category collected	Sorted for recycling yield rate (2020)	Best in-class sortation yield rate identified	2040 sortation yield rate	Comments
Clear food and beverage bottles Coloured food and beverage bottles Non-food and beverage bottles	84% [1] [2] [a]	97% [2]	**97%** [b]	The 2020 sortation rate was linearly increased up to the highest sortation rate for existing facilities sorting for PET bottles
Mono-material pots, tubs, trays (PTTs) Multi-material PTTs	20% [2][a]	n/a	**88.5%**	By 2040, the PTT sortation rate is assumed to get halfway towards the level of the best-in-class PET bottle sortation rate currently seen in Europe [c]
Other packaging (i.e. strapping, film)	~0%	n/a	**80%**	No targeted collections of film predicted to take place. For any strapping collected, sortation rates by 2040 are assumed to match those of PET bottles in 2020 [d]
Textiles	98% [3] [a]	n/a	**96%**	Sortation infrastructure is assumed to scale according to tonnages of textiles collected [e]. Sortation rates expected to decrease slightly as separate textiles collections increase and the share of contaminated/poor-quality textiles increases [f]

Sources: (1) Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate)(PET) Packaging Management Strategies in the EU,- Supporting Information A, A.Bassi et.al (2022), (2) Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers, I.Antonopoulos et.al (2021 (3) Sorting for Circularity Europe, Fashion for Good (2022), (4) PET trays recycling trial, Petcore & Paolo Glerean (2016)

Notes: (a) Refer to Figure 21 for more information.

(b) Very high average bottle sortation rates by 2040 are foreseeable considering that collection targets from the Single Use Plastic Directive (90% of bottles placed on the market) come into force by 2030, at which point most bottles will be collected via DRS and so this is likely to create a PET bottle recyclate stream of high purity and quality that requires much less sortation. By 2040, this is likely to be a mature system across Europe. Industrial-scale automated recognition and sortation technologies are also already active e.g. Recycleye, Greyparrot and True Circle.

(c) A 98% sortation rate has been seen in a small-scale trial of PTT mechanical recycling (4), though this was performed on pre-sorted bales of PTTs so it is not a true sort rate of PTTs from other mixed recyclate. PTTs are not assumed to attain the same sort rate as for PET bottles as their collection/sortation/recycling is less mature than for PET bottles (and therefore there is a more significant associated learning curve for industry), they are unlikely to be subject to DRS and they may be subject to less stringent and consistently applied design for recycling requirements (which may also make them harder to sort from other waste). The sortation rate increase here can also be seen as an indicator of downstream recycling capacity being developed, which prevents sorted PTTs from being downcycled or sent for residual waste as in 2020.

(d) There is no direct evidence to support this sortation rate. This is based upon the broader influence of the draft Plastic Packaging Waste Directive/Regulation, which is envisaged to also include strapping.

(e) This is enabled by a shift in textiles sortation for recycling from mostly manual to mostly automated, to deal with much higher tonnages of low-value separately-collected textiles received. Industrial-scale sortation facilities are already being trialled, e.g the 24,000 tonne per year Swedish Siptex sorting project, although textiles arriving at this plant have been subject to some manual pre-sorting, whereas this facility is focussed the secondary sorting stage of sorting by colour and fiber type.

(f) Additionally, as collection rates increase, an increasing amount of lower-quality textiles will be diverted from entering mixed waste, which are likely to be lower quality/more contaminated, therefore the 95% rate is kept constant.

FIGURE 23: Waste exports (Arrow Y3) - assumptions

Scenario/system state	Assumptions
All scenarios	• **Bottles / PTTs:** We assume no export of this waste is taking place due to limited evidence and that this situation persists 2020 - 2040 [1,2,a] • **Other packaging:** assume no exports take place, 2020 – 2040 • **Textiles:** 68% of collected textiles are exported for reuse in 2020 [3]. The tonnage of textiles exported is assumed to stay constant 2020 - 2040 as collections rise, aligned with the JRC assumption that most reusable textiles are already currently being collected [4] and the strategy of the EU to reduce waste exports over time through more stringent export regulations [2,5]

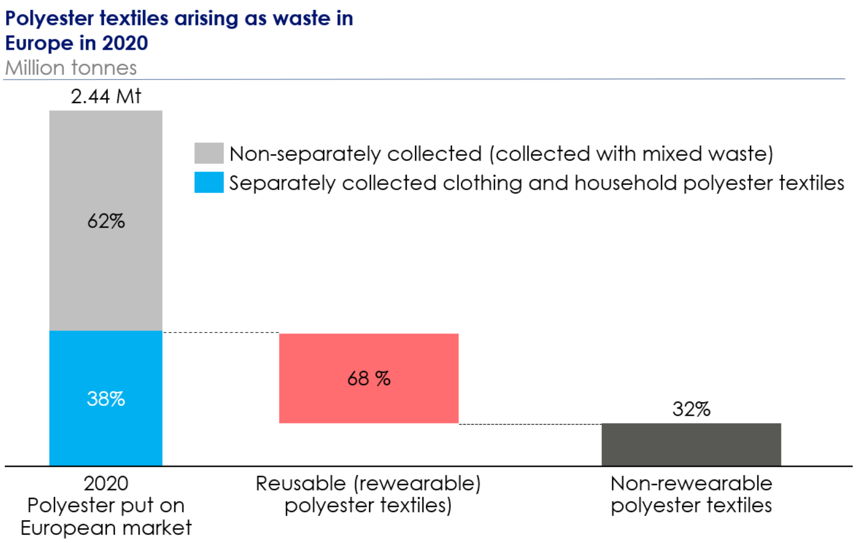
Sources: (1) PET Market: State of Play 2022, Eunomia (2022), (2), Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste, European Comission (2021) (3) Sorting for Circularity Europe, Fashion for Good (2022), (4) Circular economy perspectives in the EU Textile sector, JRC (2021), (5) Questions and Answers on EU Strategy for Sustainable and Circular Textiles, European Commission (2022), accessed 3rd February 2023,

Note: (a) The only evidence of exports determined is from source (1) and is based upon the difference between quantities of PET sorted for recycling and amounts received by recyclers, being ~3% of the quantity sorted for recycling. This could also be attributed to data errors and therefore no exports have been modelled. EC No1013/2006 also seeks to impose stricter regulations on exports of waste, in part to secure greater access to recyclate for Europe itself. Additionally, no imports of waste into the European system are modelled, nor are imports of virgin or recycled PET, or finished PET products.

Deep dive on existing evidence base for polyester textiles separate collection rates and polyester purity distribution

Data for textile was found to be the most challenging to assemble given the data gaps and the lack of consistent metrics due to the difference in value chain set up and material composition (e.g;, blends). Figure 24, 25 and 26 summarize the assumptions, data and sources used to model the textile PET system.

FIGURE 24: Polyester textiles in Europe in 2020 - overview



Assumptions

- 2.9Mt of polyester (textiles) were placed on the market in 2020. In the same year, an estimated 2.44Mt of polyester textiles are assumed to arise as waste [a].
- On average, 38% of household textiles placed on the market in Europe are separately collected for reuse or recycling [1]. Polyester-containing textiles specifically are also assumed to be collected in the same proportion as overall household textiles (38%), as they are mostly clothing and household textiles [2].
- Of the separately-collected textiles, 68% are reusable/rewearable and 32% are not [3][b]. All the reusable textiles are assumed to be exported outside of Europe to secondary reuse markets [c].

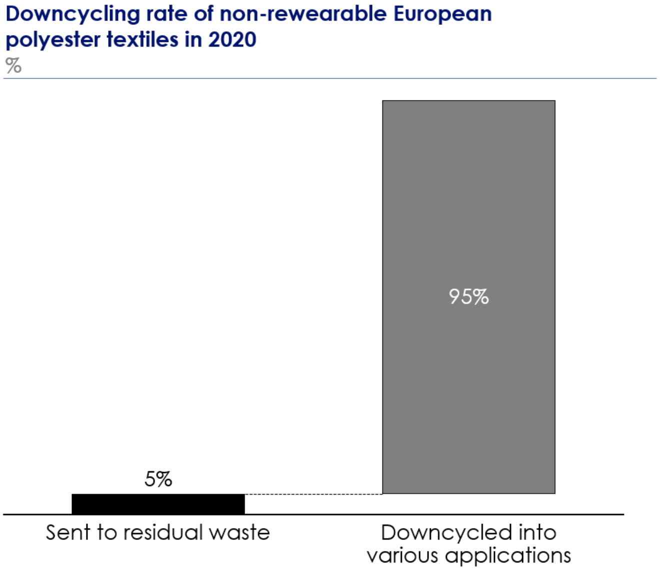
Sources: (1) Circular economy perspectives in the EU Textile sector, JRC (2021), (2) Modeling the EU plastic footprint: Exploring data sources and littering potential, A. Amadei et.al (2022), (3) Sorting for Circularity Europe, Fashion for Good/Circle Economy (2022)

Notes: (a) Refer to Table 1. Textiles are assumed to arise as waste according to a Weibull distribution where a textile item has a 5-year lifespan on average and the distribution has a shape distribution of 2.5. Consumption of polyester textiles in years prior to 2020 has been estimated by taking the 2017 - 2022 anticipated compound annual growth rate in consumption (Table 1) and applying this in reverse. The collection rate from (1) has been applied to the amount of waste created rather than placed on the market.

(b) The percentages of reusable vs non-reusable textiles arriving at European sorting facilities, as determined from (2) have been normalised since in this report the values for these categories add up to 86% in total. Additionally, as stated earlier, as separate collection rates of textiles increase over time, the tonnage of reusable textiles exported is assumed to stay constant, therefore the relative percentage of collected textiles that are reusable and therefore exported decreases over time.

(c) According to (2) a small fraction of the reusable textiles are assumed to be sold for reuse inside Europe, but these have not been modelled separately and instead are also assume to be exported

FIGURE 25: Fate of non-rewearable polyester textiles in Europe in 2020



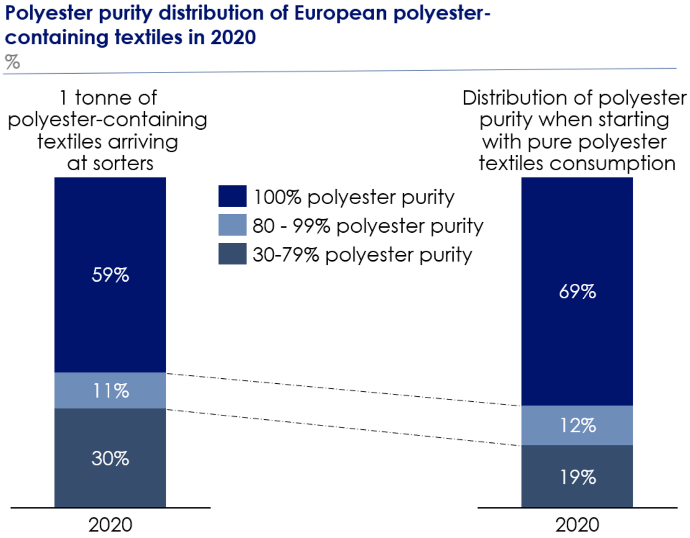
Assumptions

- ~ 5% of the non-rewearable textiles received by sorting plants are discarded as residual waste (and sent to landfill or incineration) [1]
- The remainder are downcycled into a range of applications, including insulation as well as automotive and furniture stuffing [a]
- In scenarios where waste PET depolymerisation capacity is installed in Europe, non-reusable polyester-containing textiles with a high-enough polyester content (80%+) are assumed to be diverted to depolymerisation [2].

Sources: (1) Sorting for Circularity Europe, Fashion for Good/Circle Economy (2022) and conversations with author, (2) Project Europe Update Fall 2022, Accelerating Circularity (2022)

Notes: (a) Data on the exact downcycled applications for which polyester-containing textiles are used and in which proportions is not available, however it is generally accepted that once these textiles are downcycled, and after their in-use phase during their second life, they are most likely to be sent to landfill and incineration. Additionally, all downcycling has been assumed to take place in Europe due to lack of data availability, though there may in fact be some export of this material for use outside of Europe.

FIGURE 26: Polyester purity of textiles in Europe in 2020



Assumptions

- Recent compositional analysis work [1] provides a snapshot of the polyester purity composition of polyester-containing textiles arriving at European sortation facilities (see left bar chart).
- The current study uses available data for European consumption of (pure) polyester specifically (~2.9Mt in 2020) as a starting point and tracks the flow of this material through the European system. Therefore, the composition of polyester arriving at sorters has been normalised to account for this (see right-hand bar chart).
- This (right-hand side chart) polyester purity distribution has then been assumed to be consistent across all polyester-containing textiles placed on the European market [a].

Sources: (1) Sorting for Circularity Europe, Fashion for Good/Circle Economy (2022) and discussions with the author, (2) Modeling the EU plastic footprint: Exploring data sources and littering potential, A. Amadei et.al (2022),

Notes: (a) It should be noted that the compositional study of (1) did not analyse the fibre composition of the reusable polyester textiles arriving at sorters, nor textiles as a whole when placed on the market. Instead it analysed low-value rewearable and non-rewearable/reusable textiles that were separately collected. Therefore, the assumption that the polyester purity seen in the sample can be applied uniformly across the entire market may not be accurate. Additionally, the study (1) notes that in general, items of clothing appeared to be overrepresented in the sample analysed (making up ~94% of items sampled) and household textiles were underrepresented (~6%), compared to available data from the Joint Research Centre (1) on the composition of textiles placed on the European market. As available data (2) indicates that around 30% of polyester-containing textiles consumed in Europe are household textiles, this may create additional inaccuracy in the representativeness of the polyester-containing textiles market. Another potential source of inaccuracy is that of the polyester-containing textiles within the sample, 0.1% had <30% polyester content, whereas clothing with <30% content (e.g. T-shirts) are thought to be relatively common. Finally, the compositional study was limited to samples taken from a select number of major sorters operating in some major European countries, and therefore it is possible that the results do not reflect sortation across Europe as a whole. Nevertheless, this is the most comprehensive compositional study of this type to-date and the best data available.

Feedstock allocation to recycling processes

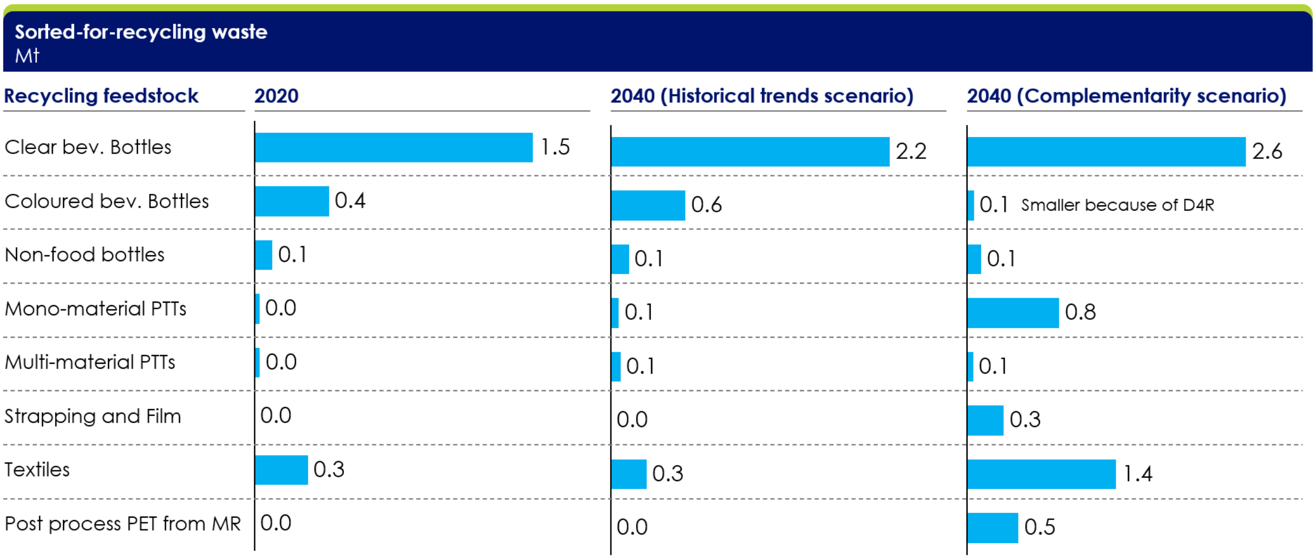
Once waste is sorted for recycling (i.e. output of Box Y), this feedstock must be allocated to different types of recycling processes. Feedstock allocation therefore refers to the specific proportions of a given type of sorted PET waste feedstock which travel along arrows F1-F5 to various types of recycling activities. Feedstock allocation is sensitive to the different grades of materials: (1) contact-sensitive and bottle-grade mechanical recycling, (2) contact-sensitive and non-bottle-grade mechanical recycling, (3) non-contact-sensitive-grade mechanical recycling and (4) mechanical downcycling in the case of textiles as well as (5) material suitable for chemical PET recycling.

It was necessary to determine a set of principles in order to create a decision-making framework that could guide feedstock allocation under different scenarios. However, it is important to note that these principles should be taken as possibilities, not as recommendations. Making recommendations will require additional consideration to a range of factors which fall outside of the scope of this study, including (non-exhaustive list):

- to what extent different feedstock allocation methodologies do/don't allow PET product producers to meet legislative targets e.g. for recycling rate, recycled content etc
- the grades of rPET created as a result of specific allocations
- the GHG emissions created as a result of specific allocations
- the extent to which certain allocations do/don't incentivise certain PET product producers to invest in their own collection, sortation and recycling infrastructure
- the geographic location of manufacture for specific product types (inside vs outside Europe e.g. textiles) as compared to where they are consumed, collected and recycled

The anticipated quantities of sorted PET waste for recycling under the different key scenarios in 2040 is in Figure 27. Clear beverage bottles, mono-material PTTs and textiles will be the primary feedstocks for recycling in the 2040 ambitious complementarity scenario.

FIGURE 27: Sorted for recycling PET volumes in the main scenarios



Note: MR = Mechanical recycling; Strapping and Film together comprise 'Other packaging category'

To guide feedstock allocation, the grades of rPET produced by different recycling activities, and which can be subsequently used in different key product categories, were categorised into four main types (Figure 27). It is acknowledged that this is a reasonable simplification of the complex reality of rPET grades. Note that these are the grades of final rPET pellets produced as the output of the following system map processes:

- Box I: (with feedstock input from arrow F1) produces contact sensitive/ bottle-grade rPET
- Box J: (with feedstock input from arrow F5) produces non-contact sensitive rPET
- Box I: (with feedstock input from arrow F4) produces contact sensitive/ non-bottle-grade rPET
- Box K: (with feedstock input from arrow F3) produces virgin-like chemical rPET
- Box R: (with feedstock input from arrow F2) does not produce rPET and instead the output is used directly within downcycled products e.g. mattress filling/stuffing, building insulation etc and is not considered recoverable to be recycled again. The

tonnage input capacity for PET feedstock downcycled is capped at the level calculated for 2020 due to anticipated market saturation: ~0.3 Mt.

FIGURE 28: rPET grades arising from each product categories

✓ rPET grade can be used to make product type

Product type	rPET grades produced by mechanical recycling: Contact sensitive Bottle grade	Contact sensitive Non-bottle grade	Non-contact sensitive Non-bottle grade	rPET from chemical PET recycling
Clear bev. bottles	✓			✓
Coloured bev. bottles	✓			✓
Non-food bottles	✓			✓
Mono-material PTTs	✓	✓		✓
Multi-material PTTs	✓	✓		✓
Textiles: 100% polyester content	✓	✓	✓	✓
Textiles: 80-99% polyester content	✓	✓	✓	✓
Strapping	✓	✓	✓	✓
Film	✓	✓	✓	✓

Notes: Strapping and Film together comprise 'Other packaging category'.

The principles used in feedstock allocation as described in Figure 29 and 30 are then used to derived specific feedstock allocation. The specific feedstock allocations (percentages of each type of feedstock) used in the different core scenarios and 2 core sensitivities (mechanical/chemical PET growth and development only) are shown in the Figure 31, 32 and 33.

FIGURE 29: Principles applied for feedstock allocation in the ambitious complementarity scenario in 2040

Mechanical recycling, 2040	▪ The opportunity for **mechanical recycling** is considered **first** ahead of chemical recycling according to the following rules:
	▪ Recycling feedstock is used to make the **highest grades** of mechanically recycled rPET possible. If the highest grade possible is the same grade as that used to manufacture the waste PET feedstock entering the recycling activity, we assume that 20% will be recycled into the next lower category due to **degradation or imperfect sorting**
	  ▪ rPET grade hierarchy followed:
	    1. Contact sensitive bottle grade
	    2. Contact sensitive non-bottle grade
	    3. Non-contact sensitive non-bottle grade
	  ▪ If a recycling process is **TRL < 7** today, it is assumed to be not possible to scale widely across Europe over the next 20 years (e.g mechanical fibre-to-fibre recycling)
	  ▪ If there is uncertainty whether production of a specific rPET grade from a specific type of feedstock will be **feasible at scale** by 2040, 50% is recycled into the rPET grade in question and 50% into the next lower grade (e.g. mechanical tray-to-tray recycling)

Chemical PET recycling, 2040	**Chemical recycling is considered when the mechanical recycling opportunity is insufficient, according to the following rule:** ▪ If, as a result of the rules above, at least 50% of the feedstock would be mechanically recycled into a lower rPET grade, then 50% of this lower-quality material (material which has not been recycled back into the same rPET grade) is allocated to chemical recycling, which is assumed to produce virgin-equivalent rPET
Change over time	▪ **Linear interpolation** between current status (2020) and recycling principles (2040)

FIGURE 30: Principles applied for feedstock allocation in the historical trends scenario and the sensitivities analyses in 2040

Historical trends scenario	▪ Recycling technology allocation and mechanical rPET grade produced is kept constant from 2020 to 2040 with the exception of clear beverages bottles ▪ Clear beverage bottles adopt the same distribution of mechanical rPET produced as the ambitious complementarity scenario since this is understood to be within current technological capabilities
Mechanical recycling growth and development only sensitivity (no chemical recycling)	▪ Mechanical rPET grade produced decided according to the same rules as for the ambitious complementarity scenario, but without any allocation to chemical PET recycling
Chemical PET recycling growth and development only sensitivity (mechanical recycling capacity maintained at 2020 levels)	▪ Fixed mechanical capacity at 2020 levels is used to generate highest possible grades of rPET, according to the same principles as the ambitious complementarity scenario (e.g. since clear beverage bottles produce the highest share of contact sensitive bottle grade rPET, mechanical recycling capacity in 2040 is prioritised for this feedstock first) ▪ Remaining feedstock is allocated to chemical recycling. Multi-material trays and coloured beverages are fully allocated to chemical recycling.
Other sensitivities	▪ Recycling technology allocation is kept the same as in the ambitious complementarity scenario. In the case of the 'No chemical PET recycling for any polyester textiles' sensitivity, quantities of sorted, recyclable textiles in excess of the flat mechanical downcycling capacity (~0.3Mt/yr) are sent to landfill and incineration.

FIGURE 31: Allocation of sorted-for-recycling waste in the historical trends scenario

CS/BG - Mechanical Recycling: Contact-sensitive / Bottle-grade
CS/NBG - Mechanical Recycling: Contact-sensitive / Non-bottle-grade
NCS - Mechanical Recycling: Non-contact-sensitive (bottle-grade and non-bottle-grade)
Chem - Chemical Recycling: Contact-sensitive / Any grade

Product type	rPET generated **2020**	rPET generated - Historic trends **2040**	Comments
Clear beverage bottles	CS / BG 39%[1]; CS / NBG 30%[1]; NCS 31%[1]	CS / BG 80%; CS / NBG 10%; NCS 10%	Mostly bottle-to-bottle recycling expected by 2040
Coloured beverage bottles	CS / BG 10%[1]; CS / NBG 45%[1]; NCS 45%[1]	CS / BG 10%; CS / NBG 45%; NCS 45%	10% bottle-to-bottle recycling today persists
Non-food-grade bottles	NCS 100%	NCS 100%	Bottles recycled to produce rPET flake for e.g strapping and textiles
Mono-material PTTs	CS / BG 10%[2]; CS / NBG 45%[2]; NCS 45%[2]	CS / BG 10%; CS / NBG 45%; NCS 45%	10% of trays recycled in bales of trays to produce bottle-grade rPET
Multi-material PTTs	CS / BG 10%[2]; CS / NBG 45%[2]; NCS 45%[2]	CS / BG 10%; CS / NBG 45%; NCS 45%	As above
Textiles: 80 - 100% polyester content	Downcycling 100%	Downcycling 100%	Non-reusable textiles are downcycled into e.g. insulation, stuffing etc
Textiles: 30 - 80% polyester content	Downcycling 100%	Downcycling 100%	As above
Strapping	No Recycling	No Recycling	No recycling expected due to lack of targeted collections and sortation
Film	No Recycling	No Recycling	No recycling expected due to lack of collections and difficulty of recycling films
Post process PET from MR	No Recycling	No Recycling	No recycling expected due to lack of appropriate recycling infrastructure

Sources: (1) PET Market: State of Play 2022, Eunomia (2022), (2) Industry association expert interviews (2023)

FIGURE 32: Allocation of sorted-for-recycling waste in the ambitious complementary scenario and the sensitivity ambitious complementarity scenario with limited waste collection and sortation

- CS/BG - Mechanical Recycling: Contact-sensitive / Bottle-grade
- CS/NBG - Mechanical Recycling: Contact-sensitive / Non-bottle-grade
- NCS - Mechanical Recycling: Non-contact-sensitive (bottle-grade and non-bottle-grade)
- Chem - Chemical Recycling: Contact-sensitive / Any grade

Product type	rPET generated **2020**			rPET generated - Comp A **2040**				Comments
	CS / BG	CS / NBG	NCS	CS / BG	CS / NBG	NCS	Chem	
Clear beverage bottles	39%[1]	30%[1]	31%[1]	90%	5%	5%		Mostly bottle-to-bottle mechanical recycling expected
Coloured beverage bottles	10%[2]	45%[1]	45%[1]		25%	25%	50%	No bottle-to-bottle recycling expected due to D4R (few bottles; small market)
Non-food-grade bottles			100%			80%[3]	20%[3]	By 2040 most bottles mechanically recycled, but some are too low quality
Mono-material PTTs	10%[2]	45%[2]	45%[2]		50%	25%	25%	By 2040 most PTTs mechanically recycled, but some are too low quality
Multi-material PTTs	10%	45%	45%		50%	25%	25%	As above, but small market due to D4R
Textiles: 80 - 100% polyester content	Downcycling 100%						100%	By 2040 high-purity polyester textiles are chemically recycled
Textiles: 30 - 80% polyester content	Downcycling 100%			Downcycling 100%				By 2040 low-purity polyester textiles too difficult to chemically recycle at scale
Strapping	No Recycling						100%	Collected/sorted strapping is chemically recycled
Film	No Recycling			No Recycling				No recycling expected due to lack of collections and difficulty of recycling films
Post process PET from MR	No Recycling						100%	Post-process PET (e.g., purge) is chemically recycled

Sources: (1) PET Market: State of Play 2022, Eunomia (2022), (2) Industry association expert interviews (2023)

FIGURE 33: Allocation of sorted-for-recycling waste in the ambitious complementary scenario without chemical PET recycling

- CS/BG - Mechanical Recycling: Contact-sensitive / Bottle-grade
- CS/NBG - Mechanical Recycling: Contact-sensitive / Non-bottle-grade
- NCS - Mechanical Recycling: Non-contact-sensitive (bottle-grade and non-bottle-grade)
- Chem - Chemical Recycling: Contact-sensitive / Any grade

Product type	rPET generated **2020**			rPET generated Mech A **2040**			Comments
	CS / BG	CS / NBG	NCS	CS / BG	CS / NBG	NCS	
Clear beverage bottles	39%	30%	31%	90%	5%	5%	Mostly bottle-to-bottle recycling expected by 2040
Coloured beverage bottles	10%	45%	45%		50%	50%	No bottle-to-bottle recycling expected due to D4R (few bottles; small market)
Non-food-grade bottles			100%			100%	Bottles recycled to produce rPET flake for e.g strapping and textiles
Mono-material PTTs	10%	45%	45%		50%	50%	Half of PTTs produce rPET for use in PTTs and half produce rPET for lower grade uses
Multi-material PTTs	10%	45%	45%		50%	50%	As above but small market due to D4R
Textiles: 80 - 100% polyester content	Downcycling 100%			Downcycling 100%			Some non-reusable textiles are downcycled into e.g. insulation, stuffing etc
Textiles: 30 - 80% polyester content	Downcycling 100%			Downcycling 100%			As above
Strapping	No Recycling			No Recycling			No recycling expected due to lack of targeted collections and sortation
Film	No Recycling			No Recycling			No recycling expected due to lack of collections and difficulty of recycling films
Post process PET from MR	No Recycling			No Recycling			No recycling expected due to lack of appropriate recycling infrastructure

Notes: (a) The total tonnage CS/NBG mechanical recycling capacity across both monomaterial and multimaterial PTTs is the same in 2040 as it was in 2020. However, the share is biased towards monomaterial PTTs as in this scenario, most multimaterial PTTs have switched to monomaterial through D4R

Mechanical and chemical PET recycling (depolymerisation) assumptions

This section provides an overview of the subprocesses considered to be involved in the various types of recycling modelled within the system map as well as the yield rates of these processes in the different scenarios and time points.

The types of recycling considered to be relevant to PET/polyester, in-scope and therefore modelled are set out in Figure 34. Note that depolymerization technologies are modelled as one single technology, the model is therefore agnostic regarding sub-technologies (e.g., methanolysis, glycolysis, hydrolysis). Some technologies have been excluded from the scope due to lack of relevance from a feedstock perspective (e.g., pyrolysis, and gasification where PET is not per se a targeted material and a fraction of the incoming feedstock) or the TRL has been evaluated below 7 (e.g., mechanical recycling of polyester fibres referred to as thermomechanical recycling, solvent-based recycling of PET specifically, thermohydrological separation of polyester from polycotton).

FIGURE 34: Overview of the recycling technologies in scope for the study

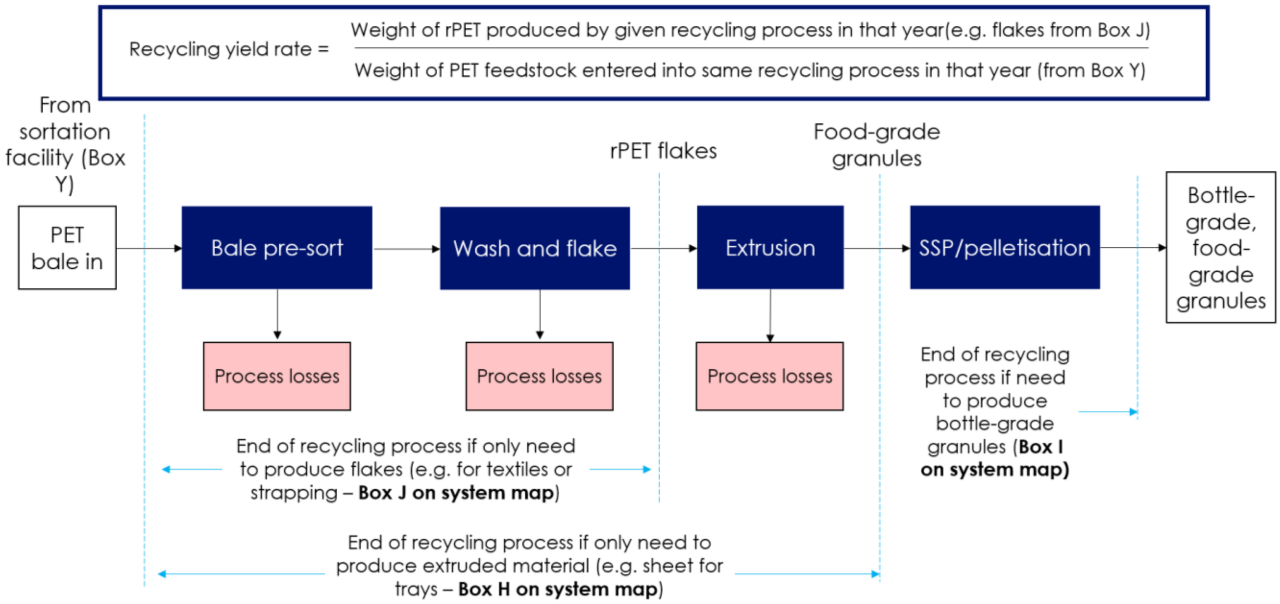
● Technologies not available or emerging for PET/polyester material-to-material recycling at scale in Europe and therefore not in-scope for this study and modelling

	Mechanical		Chemical recycling				
Recycling method	Mechanical Recycling technologies that do not significantly change the chemical structure of the PET/polyester waste feedstock and leave the polymer chain intact		Depolymerisation ('chemical PET recycling') Recycling technologies that break PET/polyester polymers down into smaller molecules (monomers or oligomers) that are reconstituted back into PET/polyester with the same properties as virgin PET			Pyrolysis The breakdown of polymers into hydrocarbons ('pyrolysis oil') and other by-products by heating to high temperatures in anaerobic conditions	Gasification The breakdown of polymers into dihydrogen and carbon dioxide ('syngas') in a controlled oxygen environment by heating to high temperatures
Sub-types + descriptions	Mechanical recycling Sortation, size reduction, cleaning and extrusion of PET/polyester waste feedstock to produce recycled PET polymers for use in new products[b]	Solvent-based recycling Processes used to dissolve the PET polymer and subsequently precipitate it again by temperature or antisolvent	Methanolysis PET/polyester depolymerisation technology using methanol as a reagent to break down PET/polyester	Hydrolysis PET/polyester depolymerisation technology using water as a reagent to break down PET/polyester	Glycolysis PET/polyester depolymerisation technology using ethylene glycol as a reagent to break down PET/polyester		

Mechanical Chemical (depolymerisation) recycling process and sub-processes

The mechanical recycling value chain is modelled as described in Figure 35. The feedstock preparation stages required before PET waste is assumed to feed into both mechanical and chemical PET recycling processes. In reality, some overlaps will exist but these may also develop as separate value chains given feedstock requirements and pre-treatments are different. Assumptions used for each process modelled are found in Figure 36 and 37. Other factors presented in Figure 38 may influence the development of yields in the future but more research is needed to understand their impact.

FIGURE 35: PET mechanical recycling value chain and sub-processes



Notes: based upon Figure 3 from Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate) (PET) Packaging Management Strategies in the EU, Andreasi Bassi, S., et.al (2022) and expert discussions

FIGURE 36: Historical trends scenario: mechanical recycling yield rates (Boxes I, J & H)

Product category	Food-grade, bottle-grade mechanical recycling yield rate (2020)	Food-grade, non-bottle-grade mechanical recycling yield rate (2020)	Non-food-grade, non-bottle grade mechanical recycling yield rate (2020)	Historic rate of increase in mechanical recycling yield rate	2040 mechanical recycling yield rate	Comments
Clear food and beverage bottles	72% (a)		75% (a)	N/a	Unchanged	Assuming no technology/ yield rate improvement by 2040 Yield rates available in the literature were silent on the relative process losses of PET vs non-PET elements
Coloured food and beverage bottles						
Non-food and beverage bottles						
Mono-material pots, tubs, trays (PTTs)	n/a	50% (b)				
Multi-material PTTs						
Other packaging (i.e. strapping, film)	n/a					
Textiles	n/a					

Sources: (1) Transition to a Circular System for Plastic, Closed Loop Partners (2021), (2) Assessing scaling effects of circular economy strategies: A case study on plastic bottle closed-loop recycling in the USA PET market, G. Loncaa, et al. (2020), (3) Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers, I. Antonopoulos et al. (2021), (4) Achieving Circularity in Norway, Systemiq (2021)

Notes: (a) Average from 9 data points from 4 different sources (1)(2)(3)(4) which are all PET-specific. Data was selected from sources known/thought to be achieving >95% rPET output purity. Data was often not product-specific, though most facilities are assumed to be taking mostly PET bottles as PTT recycling is less common. Food-grade yield rates factor in extrusion losses whereas non-food-grade yield rates are assumed not to as this is only the production of rPET flake for end uses such as strapping and textiles.

There is no available information on the fraction of the loss rates at each stage that are PET vs non-PET (contamination, non-target materials etc). Therefore, in the absence of better data, the existing yield rates have been applied to the flows of PET through the model and no adjustments have been made to account for potential contamination/non-target materials. As this assumption is applied to both mechanical recycling and *depolymerisation, it should not lead to a bias towards the favourability of one or the other. However, the overall impact is that rPET flows from the model may be a slight underestimate of the actual amounts that would be produced, if yield rates were adjusted for only PET in vs rPET created by each process.*

(b) Based upon expert input from a recycling trade association, where a range of 45-55% was given for industry yield rates, Very limited data in literature on recycling yield rates for PTTs only.

FIGURE 37: Ambitious complementarity scenarios (and relevant sensitivities): mechanical recycling yield rates (Boxes I, J & H)

<table>
<tr><th>Product category</th><th>Best-in-class food-grade, bottle-grade mechanical recycling yield rate identified</th><th>Best-in-class food-grade, non-bottle-grade mechanical recycling yield rate identified</th><th>Best-in-class non-food-grade, non-bottle-grade mechanical recycling yield rate identified</th><th>Comments</th></tr>
<tr><td>Clear food and beverage bottles</td><td colspan="2" rowspan="3">87% [a]</td><td rowspan="3">90% [b]</td><td rowspan="7">Assuming that by 2040, on average European mechanical recyclers achieve the best-in-class yield rates already seen in 2020</td></tr>
<tr><td>Coloured food and beverage bottles</td></tr>
<tr><td>Non-food and beverage bottles</td></tr>
<tr><td>Mono-material pots, tubs, trays (PTTs)</td><td rowspan="2">n/a</td><td rowspan="2">72% [c]</td><td rowspan="2">75% [c]</td></tr>
<tr><td>Multi-material PTTs</td></tr>
<tr><td>Other packaging (i.e. strapping, film)</td><td colspan="3">n/a</td></tr>
<tr><td>Textiles</td><td colspan="3">n/a</td></tr>
</table>

Sources: (1) Transition to a Circular System for Plastic, Closed Loop Partners (2021), (2) Assessing scaling effects of circular economy strategies: A case study on plastic bottle closed-loop recycling in the USA PET market, G. Loncaa, et al. (2020), (3) Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers, I. Antonopoulos et al. (2021), (4) Achieving Circularity in Norway, Systemiq (2021)

Notes: (a) Datapoint from an existing mechanical recycler of PET bottles from source (3), adjusted to include extrusion losses.

(b) Datapoint from an existing mechanical recycler of PET bottles from source (3), not adjusted for extrusion losses as not relevant.

(c) Best estimate, assuming that PTTs reach current average (sources 1-4) mechanical recycling yield rates for a similar product type (i.e. PET bottles): 72% value factors in extrusion losses, 75% value does not. Validated by expert interview with existing tray mechanical recyclers.

FIGURE 38: Mechanical recycling yield rates - other factors

Factor	Comments
Age of rPET being recycled & percentage of process input that is rPET vs vPET	No available evidence that the number of previous loops that mechanically-recycled rPET has previously been through affects recycling yield rates, even where input to the recycling process is 75% rPET, 25% virgin PET [1]. Existing research also indicates that quality metrics of rPET output are not significantly affected, though discolouration can occur [2].
Percentage of rPET to be used in end-product	There is a lack of evidence [a] that existing yield rates would be different if the rPET produced was meant to be used to manufacture products with much higher rPET content than today
Contamination	Anecdotal evidence indicates that where e.g. PTTs are included within the recycling process for bottles, they can reduce overall yield rates as PTT viscosity is lower and they produce more fines. This is considered 'built-in' to existing recycling rates [b].

Sources: (1) Circularity Study on PET Bottle-To-Bottle Recycling, E. Pinter et.al (2021), (2) Effect of recycled content and rPET quality on the properties of PET bottles, part I: Optical and mechanical properties, F. Chacon et.al (2020), (3) How circular is PET? Eunomia (2022), (4) PET Market: State of Play 2022, Eunomia (2022), (5) Effect of *recycled content and rPET quality on the properties of PET bottles, part III: Modelling of repetitive recycling, M. Brouwer et.al (2020).*

Notes: (a) There appears to be a lack of research in this area, but as noted above, existing studies (1)(2) indicate no significant impact on e.g. mechanical properties at higher percentage rPET input to the mechanical recycling process. Additionally, major German DRS organisation Petcycle already requires its bottle manufacturer members to use at least 75% rPET content in its bottles, whilst certain brands are already using 100% recycled content int their bottles (3).

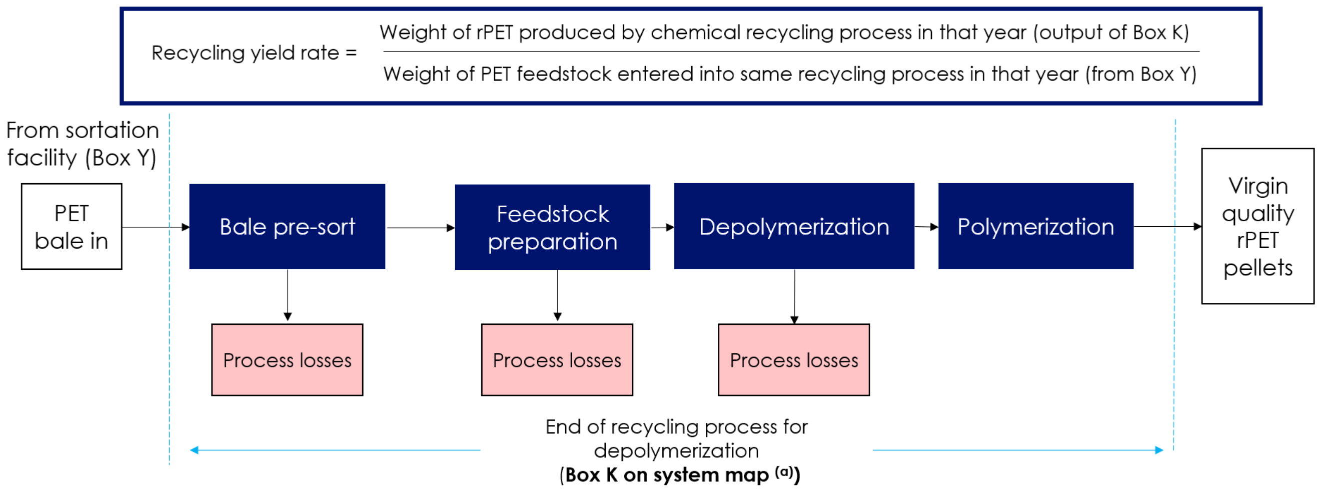
(c) Industry data (4) indicates that a small fraction of PTTs sorted for recycling are subsequently included in bottle bales sent to recyclers, and are therefore 'built-in' to existing estimates of yield rates. As dedicated PTT mechanical recycling facilities are built and most bottles move towards separate collection via DRS systems rather than comingled with other forms of packaging like PTTs, this effect is expected to decrease, contributing to the higher yield rates projected by 2040. Contamination with non-PET (e.g. other polymers or non-polymer substances) can reduce the PET purity of the rPET and therefore limit its suitability for end-uses and therefore its commercial attractiveness. Recyclers therefore spend considerable effort to remove contaminants throughout the recycling process. In terms of non-intentionally added substances (NIAS) and how harmful NIAS can accumulate and migrate from PET that is repeatedly recycled, this is an evolving area of research. Whilst the decontamination process can eliminate some NIAS (1)(5), others may accumulate, with work on harmful thresholds underway.

PET Chemical (depolymerisation) recycling process and sub-processes

The blend of chemical recycling, especially depolymerization, technologies for PET that will scale across Europe in future is a somewhat uncertain assumption, and one that should not be used as a basis for investment decisions or seen as a forecast. As a matter of fact, the model is agnostic as to which PET depolymerization will scale (e.g., methanolysis, hydrolysis, glycolysis). The chemical recycling value chain is modelled as described figure 39.

Data used for chemical recycling yields can be found in Figure 40 and 41. In both the case of the historical trends scenario and ambitious complementarity scenario (and sensitivities) it is acknowledged that available data was lacking on feedstock-specific recycling yield rates. This is an important area of future research that the industry should look to fill in order to provide greater certainty around technological capabilities.

FIGURE 39: PET chemical recycling value chain and sub-processes



- Only technologies with a TRL of 7 of higher were considered in this study, hence solvent-based purification of PET specifically (which is referred to as a chemical or physical recycling technology based on classification) was not considered in this study (1)(b)

Notes: (a) Diagram based upon figure from Transition to a Circular System for Plastic, Closed Loop Partners (2021), and expert discussions. (b) Note H&M have also funded a project with Kahatex to recover polyester from polyester/cotton blends, but given a lack of information on technology readiness, yield rates, greenhouse gas *emissions, feedstock tolerance etc, this was considered out of scope as a type of polyester recycling for the present study*

Source: (1) Uekert, T. et Al. (2023). Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics. ACS Sustainable Chemistry & Engineering.

FIGURE 40: Historic trends: chemical PET recycling yield rate (Box K)

Product category	Chemically recycled [(a)] rPET yield rate; food-grade, any application grade (2020)	Historic rate of increase in recycling yield rate	2040 recycling yield rate	Comments
Clear food and beverage bottles	82% [(a)]	**No data available**	**82%**	2040 yield rate assumes no technological improvement (i.e. no significant infrastructure improvement) Yield rates available in the literature were silent on the relative process losses of PET vs non-PET elements
Coloured food and beverage bottles				
Non-food and beverage bottles				
Mono-material pots, tubs, trays (PTTs)				
Multi-material PTTs				
Other packaging (i.e. strapping, film)				
Textiles				

Sources: (1) Transition to a Circular System for Plastic, Closed Loop Partners (2021), (2) State of Play: Chemical Recycling, Eunomia (2020)

Notes: (a) Chemical recycling within the system model refers to depolymerisation specifically (system map Box K). This process includes pre-processing stages such as sortation and size reduction, the depolymerisation stage to produce PET monomers and the (re)polymerisation process to produce PET. The yield rates are taken to be the average across all major types of depolymerisation (glycolysis, hydrolysis and methanolysis) with available data.

(b) Average from 6 data points from 2 different sources (1) (2) which are all PET-specific. However, no PET product-specific data was available. Yield rate includes available data for yield rate of pre-sorting and feedstock preparation stages (~92%) and depolymerisation reaction stage (~89%), which, when applied sequentially, give an average yield rate of 82%.

As with available yield rate data for mechanical recycling, there is no available information on the fraction of the loss rates at each stage that are PET vs non-PET (contamination, non-target materials etc). Therefore, in the absence of better data, the existing yield rates have been applied to the flows of PET through the model and no adjustments have been made to account for potential contamination/non-target materials. As this assumption is applied to both mechanical recycling and depolymerisation, it should not lead to a bias towards the favourability of one or the other. However, the overall impact is that rPET flows from the model may be a slight underestimate of the actual amounts that would be produced, if yield rates were adjusted for only PET in vs rPET of each process.

FIGURE 41: Ambitious complementarity scenarios and sensitivities: chemical PET recycling yield rates (Box K)

Product category	Chemically recycled [(a)] rPET yield rate; food-grade, any application grade (2020)	2040 recycling yield rate (best-in-class)	Comments
Clear food and beverage bottles	82% [(a)]	90% [(b)]	Assuming best in class yield rate by 2040
Coloured food and beverage bottles			
Non-food and beverage bottles			
Mono-material pots, tubs, trays (PTTs)			
Multi-material PTTs			
Other packaging (i.e. strapping, film)			
Textiles			

Sources: (1) Transition to a Circular System for Plastic, Closed Loop Partners (2021), (2) State of Play: Chemical Recycling, Eunomia (2020)

Notes: (a) Refer to Figure 40

(b) Best-in-class rate determined from data within sources (1) and (2), again, adjusted to include pre-processing losses.

Mechanical downcycling of textiles into low-grade applications

Very limited information was available on the PET/polyester textiles downcycling industry. Generally-speaking, it is understood that polyester-rich clothing is not suitable for certain downcycling applications like industrial wiping rags due to e.g. worse absorbent properties and higher likelihood of static electricity build-up and discharge than cotton-rich textiles.[6] Instead, they are more likely to be used for example as furniture or automotive stuffing and property insulation filling. However, the specific product types, relative allocations of PET to these, yield rates of manufacturing processes, product lifetimes, disposal pathways and geographic location of final products consumed are not known. Nor is the elasticity of the textiles downcycling industry i.e. how responsive it would be to increased volumes of non-reusable textiles that cannot be chemically-recycled. As the Sorting for Circularity report indicates that the cost per kg of downcycled textiles is already very low, it is assumed that this is a relatively saturated market which is unlikely to scale significantly with the arrival of significantly higher tonnages of collected/sorted feedstock.

Therefore, in all scenarios, the amount of non-reusable PET textiles allocated to downcycling is fixed by mass and is limited to a ceiling of 0.3Mt. The average lifetime of the products produced is assumed to be 10 years (an approximate average across both long-loved built-environment applications e.g. insulation and shorter-lived applications like furniture stuffing). The distribution of this waste arising also follows a Weibul distribution. Once this material subsequently arises as waste, it is assumed to all be collected (with no environmental mismanagement taking place) and sent to landfill/incineration within Europe.

[6] Sorting for Circularity Europe, Fashion for Good/Circle Economy (2022)

More work is needed to better understand this industry and the extent to which it might complement or compete with chemical PET recycling for textiles.

Residual waste and disposal

Box L: Residual Waste: Residual waste (system map box L) is the leftover waste from collection, sortation and recycling processes that cannot be treated effectively to recover PET. In Europe, collected residual waste is assumed to properly managed and therefore does not leak into the environment. As a result, Arrow L2 is set to 0.

Box M: Unsorted Managed Waste: Residual waste in the system arise from (1) waste collected as mixed waste, and which is not subsequently sorted for recycling (2) waste from clean waste sorting facility, (3) waste from recycling process losses as well as (4) waste for products reaching end-of-life using downcycled polyester textiles. The residual waste is sent to box M which then flows to a mix of landfill (Box N) and incineration (Box O). The landfill versus incineration mix changes between 2020 and 2040 as described in Figure 42. The mix of landfill and incineration in any given year is then applied uniformly across all scenarios/sensitivities.

FIGURE 42: Assumptions for residual waste and disposal

Scenario/system state	Assumptions
All scenarios	• Residual waste is the non-usable waste leftover after mixed waste collections, sortation and recycling. • Starting values for the proportions of plastics in residual waste going to landfill (36%) versus incineration (64%) in 2020 are sourced from the literature[1]. • The Landfill Directive (2018) [2] sets a target of 10% of municipal waste going to landfill in the EU by 2035. However, to maintain a consistent approach across all scenarios, the historic compound annual rate of change in the ratio of plastic waste being sent to landfill as compared to incineration in Europe 2010-2020 was determined from the literature [3] (-4.4% per year) and this rate was then extended to 2040. As landfill comprised 36% of waste disposal in 2020, the rate in 2040 is modelled as 15%, with the remaining 85% being incinerated. • It is assumed that no residual waste is mismanaged (i.e. leaks into the environment)[a].

Source: (1) Reshaping Plastics: Pathways to a Circular, Climate Neutral Plastics System in Europe, Systemiq (2022), (2) DIRECTIVE (EU) 2018/850 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste, (3) Plastics – The Facts 2021, Plastics Europe (2022)

Notes: (a) This refers to managed residual waste, some mismanagement does occur after waste is initially created e.g. consumer littering.

Allocation of rPET produced to production of new products

Once PET/polyester feedstock has been allocated to recycling processes and subsequently been recycled to produce different grades of rPET as previously defined, this rPET is made available within the model for the production of new PET products in the next year.

When stating whether rPET can meet and/or exceed PPWR rPET content targets, analysis was based upon relevant grades of rPET produced versus the product categoriy production needs according to PPWR rPET targets for each.

Allocation of rPET to production of new product has no incidence on the rest of the analysis especially for the sub-sequent life of the PET. Therefore, the models does not track PET average age and relative limit to the use of rPET for more than one cycle. More academic research is necessary to state if that could rise to limitations from the PET system.

4. Model assumptions for Greenhouse gas (GHG) emissions

To estimate the environmental impacts of the different scenarios evaluated, the calculation of GHG emissions (in tonnes of carbon dioxide equivalent; tCO_2e) from each stage of the process is integrated throughout the materials' flow model. To achieve this, each of the processes or activities relating to PET/polyester and contained in the system map is associated with an emission factor per unit of PET material processed (i.e., per tonne of PET entering the process/activity). The emissions across all activities and PET categories are then summed up in a given year to give the system GHG emissions for that year and scenario. Figure 43 presents the consolidated GHG emission factors per unit of PET material used in the model, corresponding to their estimate for the year 2020, together with the bibliographic sources from which these values were obtained.

FIGURE 43: Consolidated GHG emission factors used for modelling purposes

MAGNITUDE PER PROCESS/FLOW (PRESENT VALUE)
End of range shows textiles
Credits from energy or material savings

	Emission factors (2020)		Units	Explanation
Production & consumption	virgin prod	2.2	tCO_2/t_{output}	Cradle to Gate LCI assessment, published by Plastic Europe Eco-profiles, 2017
	conversion	0.4 – 14.0	tCO_2/t_{output}	Packaging: European Topic Centre on Waste and Materials in a Green Economy (2021); Textiles: Wrap 2012
	elimination	0.0	$tCO_2/t_{eliminated}$	Plastics IQ, 2021; estimations and assumption applied to other Systemiq studies (e.g. Reshaping Plastics)
	reuse	1.4	tCO_2/t_{reused}	Plastics IQ, 2021; estimations and assumption applied to other Systemiq studies (e.g. Reshaping Plastics)
	substitution	0.9 – 1.5	$tCO_2/t_{substituted}$	Plastics IQ, 2021; estimations and assumption applied to other Systemiq studies (e.g. Reshaping Plastics)
Collection & sorting	collection	0.0	tCO_2/t_{input}	Deloitte for Plastic Recyclers Europe, Germany (Blueprint for plastics packaging waste: Quality sorting & recycling, 2015); applied to
	sorting	0.1	tCO_2/t_{input}	Deloitte for Plastic Recyclers Europe, Germany (Blueprint for plastics packaging waste: Quality sorting & recycling, 2015)
	export	1.3	tCO_2/t_{input}	Calculation considering EOL world mix average (Breaking the Plastic Wave, 2020)
Recycling	mechanical_recycling	0.4	tCO_2/t_{output}	Deloitte for Plastic Recyclers Europe, Europe (Blueprint for plastics packaging waste: Quality sorting & recycling, 2015);
	Chemical PET recycling	1.7	tCO_2/t_{output}	Environmental and economic assessment of plastic waste recycling (JRC Technical Report, 2023)
Disposal	incineration	1.4 – 2.3	tCO_2/t_{input}	Environmental and economic assessment of plastic waste recycling (JRC Technical Report, 2023) ; considers grid emissivity for savings (EEA proj. 2020-30)
	landfill	0.0	tCO_2/t_{input}	Study about the carbon footprint of scotland's waste (Zero Waste Scotland, 2016)

In order to arrive at this set of GHG emissions factors, assumptions were needed about the system. The first set of assumptions refers to the scope of the analysis and a second one to the calculation methods, particularly in cases in which the data identified in the literature required adaptations to make these operable in the European PET flows model.

The assumptions made in relation to scope include:

i. Scope 3 GHG emissions associated with the use of PET/Polyester products (e.g. the wearing and washing of polyester textiles by consumers) are not accounted for.
ii. The process 'Design for recycling' does not generate GHG emissions.
iii. GHG emissions from transportation of imported/exported materials are not considered.

iv. 100% of the outputs from PET depolymerization processes are constituted by monomer precursors for the production of PET. The production of other by-products or chemicals are not modelled and therefore there are no GHG emissions associated with any non-PET polymer depolymerization process outputs.
v. Mismanaged waste does not generate GHG emissions. Open burning of waste is not understood to be a significant practice in Europe and PET waste that leaks into the environment is not considered to generate GHG emissions.
vi. Each GHG emission factor reported represents the absolute emissions resulting per process, without including any related credits or savings (e.g. savings from energy production or other inputs of substituted materials). Only one exception is made, which is for the incineration of PET. Since the energy produced by this process in Europe is used to produce electrical energy, or in some cases for heating energy, this emission factor considers the savings in GHG emissions that would otherwise be generated by conventional means to produce the equivalent energy or heat equivalent derived from the incineration process.

The assumptions made in relation to the calculation methods for the emission factors are:

i. For emission factors with low certainty or high variability in the literature, several sources were considered and the reference with the central or most representative value was selected. Averages using values across different sources were not calculated. Note however that for the emissions associated with chemical PET recycling, an intra-source average value was calculated across the different sub-types of chemical PET recycling
ii. The change in emission factors over time (2020-2040) was estimated according to the following considerations:
    a. Emission factors are impacted by decreasing emissivity from EU electricity grid mix due to the anticipated rate of adoption of renewable energy sources.
    b. Incineration is the only emission factor expected to increase over time given that energy savings due to energy generation from waste-to-energy decrease as the electricity grid decarbonises and this waste-to-energy becomes less beneficial.
    c. Electrification of processes within the system's map is held constant i.e. processes do not become increasingly electrified over time, where they were not before.
    d. Carbon capture and storage/utilisation is not considered.
    e. Emissions factors are applied consistently across all the modelled scenarios.

Below we present in greater detail the calculations used to arrive at the GHG emission factors used in the model. Additional explanation is only provided for values which required additional adaptation to be used in the model. For those cases in which the data provided by the literature could be directly entered into the model, the GHG emissions factor and their respective source are described in the figure above showing the summary table and sources.

GHG emissions for conversion processes

The GHG emission factors for conversion processes correspond to the emissions generated by the transformation PET/Polyester into final products. These processes begin by taking the PET material (usually in pellet form) as input and finalize with an end product of this polymer.

Figure 44 describes the emission factors used to estimate the conversion of PET into packaging products.

FIGURE 44: GHG assumptions for conversion processes per packaging product category

Packaging product	Emission factor (t_{CO2}/t_{Output})	Explanation	Source
Bottles	0.92	Reported GHG emissions for Blow mould processing (Europe)	European Topic Centre on Waste and Materials in a Green Economy, EEA, 2021
PTTs	0.64	Average value between reported GHG emissions for: Injection mould processing (Europe)= 0.96 t_{CO2}/t_{Output} Calendering rigid sheets (Europe)=0.32 t_{CO2}/t_{Output}	European Topic Centre on Waste and Materials in a Green Economy, EEA, 2021
Other PET packaging	0.42	Reported GHG emissions for Extrusion of plastic film (Europe)	European Topic Centre on Waste and Materials in a Green Economy, EEA, 2021

For the case of conversion into textiles products, several sources were identified, and a middle value at 14.0 t_{CO2}/t_{Output} was selected as the GHG emission factor for this process. The data and the different sources collected are described in Figure 45.

FIGURE 45: GHG assumptions for conversion processes for textiles

Product	Emission factor (t_{CO2}/t_{Output})	Explanation	Source
Textiles conversion Fiber to Fabric Reference #1	12.3	Spinning and texturing: 0.55 kg CO_2/ t-shirt Knitting/Weaving: 0.28 / 3.78 kg CO_2/ t-shirt Pre-treatment: 0.39 kg CO_2/ t-shirt Dyeing and Finishings: 1.2 kg CO_2/ t-shirt (emissions from garment production removed) T-shirts per kg of polyester: 2.9	Materials Systems Laboratory Massachusetts Institute of Technology Cambridge, MA 2015

Textiles conversion Fiber to Fabric Reference #2	14.0	Fiber production (without virgin PET production): 3.2 kg CO_2/ kg fiber Yarn production: 2.7 kg CO_2/ kg fiber Fabric production: 8.2 kg CO_2/ kg fiber	WRAP UK, 2012
Textiles conversion Fiber to Fabric Reference #3	18.7	Fiber production (without virgin PET production): 9.7 kg CO_2/ kg fiber Yarn production, dyeing, weaving and knitting (emissions from garment production removed): 9.0 kg CO_2/ kg fabric	Ellen MacArthur Foundation, 2017 (Calculations by McKinsey)

GHG emissions for elimination, reuse or substitution of PET materials

The GHG emission factors for the elimination, reuse or substitution processes correspond to the emissions generated by all those processes that result in a reduction in the use of PET/Polyester products. Despite the fact that all these measures are carried out with the aim of producing a positive environmental effect (whether in terms of GHG emissions or by reducing leakage or plastic pollution), their application may result in the generation of GHG emissions. , although regularly lower compared to the use or application of PET/Polyester that are having an impact.

Since there are a large number of measures to promote the reduction in the consumption of PET via elimination, reuse or substitution, the estimated GHG emission factors correspond to the emissions generated by a series of real cases, already present in the market, which are of special relevance or have a high potential to be expanded. Figure 46 shows the selected cases in detail together with the estimates and associated bibliographic sources.

FIGURE 46: GHG assumptions for elimination, reuse and substitution

Reduction lever	Product	Emission factor (t_{CO2}/t_{Output})	Explanation	Source
Elimination	Packaging - Bottles & PTTs	0.0	Elimination of bottles through use of water glasses or others, utilization of solid products instead of liquids. Elimination of PTTs through shorter supply chains, use of coatings	Plastics IQ, 2021
	Textiles	0.0	Elimination through reduction of pre-consumer waste and over production	Plastics IQ, 2021

Reuse	Packaging - Bottles & PTTs	1.4	Average reduction in emissivity against virgin production & conversion of four case studies: Loop: -34%; MIWA: -46%; SodaStream: -87%; Coca-Cola refill bottle: -47%	Plastics IQ, 2021
	Textiles	0.0	Emissions for reuse processing (collection, washing) are not relevant and assumed as negligible	Plastics IQ, 2021
Substitute	Packaging - PTTs	0.9	Estimations produced for substitution with corrugated paper material	Plastics IQ, 2021
	Textiles	1.5	Estimations produced for substitution with PLA polymers	Plastics IQ, 2021

GHG emissions for exported materials

This GHG emission factor corresponds to those emissions produced by PET/Polyester products that are exported outside of Europe, mainly in the form of waste. Because the destinations for this type of material are diverse, the estimates in GHG emissions correspond to the average distribution of plastic waste treatments. The Breaking the Plastic Wave report (Systemiq & Pew Charitable Trusts, 2020) makes an estimate of these destinations, together with the emission factors associated with each one. Figure 47 shows the calculation of the GHG emissions factor as a weighted average of the various end-of-life destinations for these materials.

Figure 47: GHG assumptions for exported waste

EOL destinations – World Average			GHG emission factors (tCO_2e/t exported)		Weighted GHG emission factors (tCO_2e/t exported)
Landfill	37%	×	0.01	=	0.01
Dumpsite	8%	×	0.01	=	0.01
Open burning	43%	×	2.89	=	2.89
Environmental leakage	7%	×	0.00	=	0.00
Ocean leackage	5%	×	0.00	=	0.00
	100%				1.25 Weighted average

GHG emissions for depolymerization

The GHG emission factor for depolymerization corresponds to an average of the four main available technologies that show the greatest potential for commercial expansion: methanolysis, glycolysis, hydrolysis and enzymatic hydrolysis (this is taken as a separate technology to regular hydrolysis because the biological nature of this process generates significant differences in emissivity).

Various sources with evaluation of the environmental impacts on the depolymerization of PET were identified, however, one source was prioritized to obtain this information, which was the technical report produced by the Joint Research Center (JRC) published in 2023 entitled: Environmental and Economic assessment of plastic waste recycling. This report includes the evaluation of 3 of the 4 depolymerization technologies (Methanolysis-Hydrolysis, Glycolysis, Alkalyne Hydrolysis) listed under comparable conditions and in line with European protocols for this type of study. The results of this publication had to be adapted to be used in the material flow model of this study, for the following reasons:

1. Emissions in JRC report were estimated for a ton of waste with 84% PET content (weight) as input. The data required was adapted to reflect 100% rPET as output.
2. System boundaries for 2 depolymerization processes required complementing. Measurements for Methanolysis-Hydrolysis and Alkaline Hydrolysis stopped at the production of PET precursors (TPA + EG), emissions for repolymerization and finishing stages (up to the production of rPET pellets) were therefore added in order to align with the process boundaries for other types of chemical PET recycling.

Two additional sources were incorporated to integrate the GHG emissions factor for the enzymatic hydrolysis technology. For this case, two academic studies produced in the United States of America were used. These numbers were adapted to reflect a lower emissivity of the European grid compared to the USA due to a greater representation of low carbon sources for energy production. Finally, an average of both data was taken as the GHG emission factor.

Figure 48 shows the results of these calculations, as well as the average of the 4 technologies that was taken as the GHG emission factor for the PET depolymerization process. The 4 technologies are averaged without weight assuming that all four have the same potential for expansion in the near future.

FIGURE 48: GHG assumptions for depolymerization processes

Technology	Source	Emission factor - published	Explanation	Emission factor - adjusted	Adjustments
Methanolysis-Hydrolysis	JRC, 2023	1.0 ($t_{CO2}/_{Input}$)	- Emission factor per tonne of waste containing 84% PET (weight)(as input) - Includes processing energy and materials up	1.6 (t_{CO2}/t_{Output})	- Increase to 100% PET waste linearly - Translate to output assuming 82% yield[1]; assuming 100% output are PET monomers - Complement boundary to PET pellet production: +0.2 kg CO2/kgPE[2]

			to TPA+EG production		
Glycolysis	JRC, 2023	0.4 (t_{CO2}/t_{Input})	- Emission factor per tonne of waste containing 84% PET (weight)(as input) - Includes processing energy and materials up to PET granulate production	0.6 (t_{CO2}/t_{Output})	- Increase to 100% PET waste linearly - Translate to output assuming 82% yield1assuming 100% output is rPET - No boundary complement. Granulate production assumed same as pellet production
Alkalyne Hydrolysis	JRC, 2023	1.2 (t_{CO2}/t_{Input})	- Emission factor per tonne of waste containing 84% PET (weight)(as input) - Includes processing energy and materials up to TPA+EG production	1.9 (t_{CO2}/t_{Output})	- Increase to 100% PET waste linearly - Translate to output assuming 82% yield[1]; assuming 100% output are PET monomers - Complement boundary to PET pellet production: +0.2 kg CO2/kgPE[2]
Enzymatic Hydrolysis	Taylor U. et al. (2023)	4.0 (t_{CO2}/t_{Output})	- Includes processing energy and materials up to PET pellets - Emissions factors produced in USA	2.8 (t_{CO2}/t_{Output})	- Correction to EU grid. Assuming 60% electricity contribution to GHG emissions. -33% reduction in emission intensity[3] - Average between 2 technologies
	Gracida-Alvarez U et al. (2023)	3.0 (t_{CO2}/t_{Output})			
Average depolymerization				1.7 (t_{CO2}/t_{Output})	

GHG emissions for incineration

The GHG emission factor for this process corresponds to those produced by the burning of PET/Polyester waste materials, which represents one of the main destinations today for waste produced in Europe. In line with the practices of the region, the heat energy produced in this process is used to generate electricity or heating. The use of this energy for applications is outside the PET/Polyester system and is not modeled in this study. For this reason, the emissions avoided for the production of electrical energy or heating that would otherwise have occurred by conventional means (e.g. direct electrical energy production by the

European grid, heat generation through natural gas combustion) are incorporated. to the GHG emissions factor in the form of credits. There are various sources that report this data for the combustion of PET/Polyester materials, however the source produced by the (JRC), Environmental and Economic assessment of plastic waste recycling (2023), was prioritized again due to the adherence of this study to European protocols for the production of this type of data. Again, the published data required adjustments for the following reason:

1. Emissions in JRC report were estimated for a ton of waste with 84% PET content (weight) as input. The data required was adapted to reflect 100% rPET as output.

Figure 49 shows the consolidation of adjustments and the final result of the GHG emissions factor for this process.

FIGURE 49: GHG assumptions for end-of-life treatments

Process	Emission factor	Explanation	Source
Incineration	2.1 (t_{CO2}/t_{input})	- GHG emissions resulting from incineration of PET waste containing 84% PET (weight)	JRC, 2023
	2.3 (t_{CO2}/t_{input})	- Mathematical estimation of GHG emissions $$GHG_{incineration} = SW \cdot CR_{PET}/CR_{CO_2}$$ CR_{PET}=0.625 kgC/Kg_{PET} CR_{CO2}= 0.27 kgC/kg_{CO2}	Gracida-Alvarez et al. (2023)
	2.6 (t_{CO2}/t_{input})	- GHG emissions resulting from incineration of PET bottles waste	Bassi et al. (2023)
	-0.9 (t_{CO2}/t_{input})	- Energy and Materials savings from incineration of PET waste containing 84% PET (weight) - Linearly increased to meet same proportion as Gracida-Alvarez (2023) reference vs JRC 2023	JRC, 2023