S Y S T E M I Q

Circularity of PET/polyester packaging and textiles in Europe

– Synthesis of published research

February 2023

About this synthesis report

This synthesis report is the first in a series exploring circularity pathways for PET/polyester.

It draws on insights from existing published reports and research to assess the current state of PET/polyester circularity in Europe and explore the role that chemical recycling – currently utilised in very low volumes – could play in complementing mechanical recycling, reuse and other circular economy approaches. The study team would welcome questions, challenges, relevant data points and information about published or ongoing studies that are not referenced in this paper. Please contact us at **plastic@systemiq.earth**.

The next report in the series will be published in the coming months. It will provide a new evidence base, exploring the future potential for complementarity of mechanical and chemical recycling of PET in Europe under different scenarios. It will quantify material flows and environmental impacts of each scenario, and in doing so will help to answer some of the key gaps in existing research, identified in this paper.

About Systemiq

Systemiq was founded in 2016 to drive the achievement of the Paris Agreement and the UN Sustainable Development Goals, by transforming markets and business models in four key systems: land use, circular materials, clean energy, and sustainable finance. A certified B Corp, Systemiq works to unlock economic opportunities that benefit business, society, and the environment; it does so by partnering with industry, financial and government institutions, and civil society.

In 2020, Systemiq and The Pew Charitable Trusts published "**Breaking the Plastic Wave: A Comprehensive Assessment of Pathways Towards Stopping Ocean Plastic Pollution**" – a first-of-its-kind model of the global plastics system that describes how to radically reduce ocean plastic pollution. In 2022, Systemiq published "**ReShaping Plastics**", outlining pathways to a circular, climate neutral plastics system in Europe. Find out more at **www.systemiq.earth/**.

Disclaimer

This report was prepared by Systemiq with strategic guidance from an independent Steering Group with representation from the public sector, civil society and industry. While the report was financed by Eastman and Interzero, the Steering Group helped ensure its independence and unbiased nature. Responsibility for the information and views set out in this publication lies with the author. Steering Group members or funders cannot be held responsible for any use which may be made of the information contained or expressed therein and the statements and views presented in this report do not necessarily reflect those of any individual or organisation associated with this project.

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Executive summary

Since its discovery in the 1940s, the polyethylene terephthalate (PET) molecule has become a key building block for plastic packaging and polyester textiles. It has valued uses across many industries, including food and beverages, healthcare, homeware and synthetic fibres in apparel or other industries.

In the past decade, governments, civil society and industry have focused on plastic packaging and textiles as archetype sectors for the application of circular economy approaches, to reduce plastic waste and micro-plastic pollution and mitigate greenhouse gas (GHG) emissions. Circular economy approaches considered in this synthesis include reduction of avoidable material usage, reuse of products or packaging, mechanical and chemical recycling, re-design of products and packaging to be more durable or more suitable for reuse and recycling and substitution to materials with improved environmental performance.

Three research findings are highlighted in this synthesis study:

1. **The PET/polyester system in Europe is mostly not circular today, and is predominantly dependent on virgin production using fossil-fuel-based feedstocks.**
2. **Chemical recycling technologies for PET /polyester can increase circularity by complementing mechanical recycling and upcycling hard-to-recycle plastic waste into high-quality recycled PET/polyester.**
3. **Complementary application of mechanical recycling, chemical recycling and reuse in the PET/polyester system has potential to optimise environmental and socioeconomic benefits.**

1.

The PET/polyester system in Europe is mostly not circular today, and is predominantly dependent on virgin production using fossil-fuel-based feedstocks

PET/polyester is one of the three largest plastic types consumed in Europe, with around 7-8Mt consumed annually[1–3]. It is the primary plastic used in single-use plastic bottles, food trays and synthetic textiles.

- **On average, three-quarters of all PET/polyester that is put on the market ends up as waste and is not recycled** (it is landfilled, incinerated with energy recovery, or littered)[2]. This means that more than three-quarters of the new PET/polyester used each year is coming from fossil-fuel-based feedstocks (crude oil and natural gas).
- **Beverage bottles account for just under half of European PET/polyester consumption. The remainder is primarily used to make textiles** (~35%) **and trays** (~15%, also including 'pots' and 'tubs', depending on local definitions)[2]. Less than 10% of all polyester textiles and less than 20% of PET food trays put on the market are recycled[a].
- **Reuse of PET packaging is not happening at scale in Europe**, apart from a few examples, such as PET beverage bottle reuse systems operating in Germany, where they account for 15% of bottles in the water segment[4]. In Europe, re-sale of polyester apparel in second-hand markets happens for ~20% of total consumer household textiles volumes[b,5].
- **Current PET/polyester recycling rates are primarily being achieved through mechanical recycling of PET bottles** (washing, melting and re-moulding into new products). Clear PET beverage bottles are well suited to mechanical recycling and claim industry-leading performance with 50-55% recycling rates on average[2] (compared to 32%-38% reported for all plastic packaging[6,7]). This reaches higher than 90% recycling rates for clear PET beverage bottles in countries with well-performing deposit return systems (e.g., Germany or Norway)[4]. Of the 50-55% of PET bottles that get recycled in Europe, **approximately one-third of these are recycled back into bottles and the rest are recycled into other applications such as textiles or trays**. This means that around 17% of bottles put on the market are recycled into another bottle[2]. The current market dynamic, where more bottles are recycled into other applications than back into bottles, is in part a result of treatment needs to achieve required recycled PET specifications as well as relative willingness to pay for recycled PET.
- **Government policies[c] and voluntary commitments[8,9] from companies in the consumer goods and fashion sectors are creating significant pressure to increase PET/polyester recycling, particularly into contact-sensitive applications.** Governments are introducing supportive measures, such as eco-design requirements, separate collection of packaging and textiles and financing from extended producer responsibility schemes[10–13]. High market prices for contact-sensitive recycled PET (often above virgin PET prices) indicate high demand and supply constraints from the existing PET recycling system. Meeting policy and voluntary targets and industry demands will require a rapid scale-up of supplies of high-quality recycled PET/polyester in the coming years, together with the expansion of systems that collect and sort PET/polyester for recycling and minimise contamination.

a Figures represent share available for recycling.[4,5,28] Actual recycling rates are not published but expected to be much lower.
b An estimated 38% of all apparel in Europe is collected separately after consumers dispose of it, and 55% of this is then sold as re-wearable textiles[5].
c Examples: Packaging and Packaging Waste Regulation (PPWR), Loi Anti-gaspillage in France.

2.

Chemical recycling technologies for PET/polyester can increase circularity by complementing mechanical recycling and upcycling hard-to-recycle plastic waste into high-quality recycled PET/polyester.

Chemical recycling technologies rely on chemical manufacturing processes to recycle plastic by breaking down plastic polymers into smaller molecules, which can be reconstituted back into plastics with the same properties as new plastics. Chemical recycling is also known as 'molecular recycling'.

- **The molecular structure of PET/polyester is particularly suited to a type of chemical recycling known as depolymerisation**. Depolymerisation breaks down PET/polyester waste into its chemical precursors, monomers, that are then re-polymerised back into virgin-quality recycled PET or polyester.
- **Life cycle assessments indicate that depolymerisation results in lower GHG emissions than conventional PET manufacturing and waste disposal routes in Europe, although higher GHG emissions than mechanical recycling**. Depolymerisation has the potential to complement mechanical recycling through its ability to process many PET/polyester products, which are hard-to-recycle into high value recycled PET with current mechanical technologies. These include trays, coloured bottles and textiles as well as waste PET from the mechanical recycling process.
- **PET is suitable for both mechanical and chemical recycling and has unique advantages for complementary application of these technologies, compared to other plastics**. Unlike PET, chemical recycling of polypropylene and polyethylene plastics relies on pyrolysis or gasification technologies (generally higher energy requirements and lower material-to-material yields than depolymerisation) or solvent-based recycling (classified as 'novel technology', which requires a specific compliance process for the production of contact-sensitive recycled plastics for the EU market)[d].
- **Scale-up of PET/polyester chemical recycling alongside mechanical recycling is needed to achieve high overall recycling rates and decouple from fossil-fuel-based feedstocks**. Studies and industry guidance show that repeated or contaminated mechanical recycling loops can degrade the functional properties and colour of the recycled plastic. The technical limits of multiple mechanical recycling loops have not been well studied, with one laboratory study suggesting that 25% virgin-equivalent PET should be added to recycled PET to maintain polymer performance. In real-world conditions the percentage virgin-equivalent PET "recharge" to maintain performance over time may be higher than 25%. More research is needed. Chemical PET recycling is a potential source of virgin-equivalent PET[14].
- **Industrial-scale PET/polyester depolymerisation facilities have recently been announced in Europe.** These include Eastman's facility (160,000 tonnes per year)[15], Axens/Toray Films Europe (80,000 tonnes per year)[16], Infinite Loop/Group Suez facility (70,000 tonnes per year)[17], Carbios/Indorama Ventures (50,000 tonnes per year)[18], all of them to be located in France and Ioniqa's facility in the Netherlands (10,000 tonnes per year)[19].

Note: Planned depolymerisation capacity is based on publicly available information, it is unknown if projects from technology providers have final investment approval.

d Solvent-based recycling, which is sometimes referred to as chemical recycling (e.g., by the European Commission), is classified as 'novel technology' according to EU No 2022/1616; depolymerisation technologies would not be required to comply with EU No 2022/1616 assuming they can produce monomers regulated by No 10/2011 at high levels of purity.

3.

Complementary application of mechanical recycling, chemical recycling and reuse in the PET/ polyester system has potential to optimise environmental and socioeconomic benefits

Research studies show that there is no single “silver bullet” solution to building a circular economy for PET packaging and polyester textiles.

- **Reduction efforts are essential but must be selectively applied to avoid unintended environmental or social consequences**, such as food waste or climate impacts. Scale-up of reuse/resale can play a significant role (including reusable PET/polyester products) but is limited by the consumer behaviour shifts and infrastructure required. Substitution measures are also important to reduce GHG emissions, both away from and into PET/polyester.
- **Mechanical recycling is a proven and scaleable technology but struggles to convert some PET/polyester products into high-value or contact-sensitive recycled PET**, and will require a continued injection of virgin-equivalent PET to maintain polymer performance at scale.
- **Chemical PET/polyester recycling is also not a silver bullet solution**. Research studies point to the potential for complementary application of mechanical recycling, chemical recycling and reuse in the PET/ polyester system. This could achieve high recycling rates, scale up supplies of high value and contact-sensitive recycled PET, reduce greenhouse gas emissions, plastic waste and environmental pollution, and support industrial development and green job creation. Achieving this circular vision would also provide an example for complementary application of circular economy approaches in other parts of the packaging and textiles systems, and beyond.

Overall, a synthesis of 80+ research reports did not identify a system-level modelling study for the PET/polyester system that would allow for a system-level assessment of the environmental impacts from different scenarios for complementary application of reduction, reuse, substitution, mechanical recycling and chemical recycling. This task will be addressed in a follow-up report, to be published in 2023.

Methodology

A literature review was carried out across 80+ relevant studies in peer-reviewed academic journals, publications from government agencies and publications from consultancies, think-tanks and civil society organisations.

Research insights outlined in this synthesis paper are aimed at summarising what is known, what is not and key questions to develop in subsequent studies about the new PET circular system in Europe. Insights were triangulated across multiple studies or verified with industry experts. In addition to multiple peer-reviewed academic papers that focus on particular elements of the system, nine system-wide studies were particularly relevant for this synthesis:

Systemiq (2022)

Eunomia (2022)

McKinsey & Global Fashion Agenda (2020)

McKinsey (2022)

Eunomia (2020)

Eunomia & Zero Waste Europe (2022)

Systemiq & Pew Charitable Trusts (2020)

Ellen MacArthur Foundation (2016)

Closed Loop Partners (2021)

Set of key academic publications on PET recycling

Research insights outlined in this synthesis paper were triangulated across multiple studies or verified with industry experts.

Contents

State of play

for PET packaging and polyester textiles in Europe

1.1

Introduction to PET/polyester

Plastics are valued materials that have grown to play a central role in our food, consumer products, healthcare, textiles, automotive and construction sectors over the last decades.

The PET plastic molecule has proven particularly useful in packaging applications (e.g., beverage bottles and trays) due to its durability, barrier properties and because it is lightweight. It is equally valuable as a versatile and affordable fibre for weaving into textiles, used in apparel, carpets, homeware and automotive uses.

PET/polyester accounts for ~20-25% of plastic packaging and ~70-90% of synthetic textiles consumed in Europe (Exhibits 1-3). However, growing societal concerns about plastic waste, greenhouse gas emissions and micro-plastic pollution have led governments in Europe to introduce regulations to reduce waste and promote circular economy approaches. Packaging and textiles have been a particular focus for governments, because they make up a significant portion of the municipal waste stream and polyester textiles have been identified as a fast growing source of primary micro-plastic pollution[20].

PET/polyester accounts for ~20-25% of plastic packaging and ~70-90% of synthetic textiles consumed in Europe.

Exhibit 1

Overview of PET properties and applications

Names	Symbols	Physical properties	Applications
Polyethylene terephthalate (PET)	1 PET	Lightweight	Bottles when injection and stretch blow-moulded
Polyester *(in fiber form)*	1 PETE	Durable	Pots, tubs and trays when thermoformed
		Good gas barrier	Textiles, woven fabric, ropes and line when spun into fibres
		Colourless	Other: strapping, films etc.
		Safe for food contact	

Exhibit 2

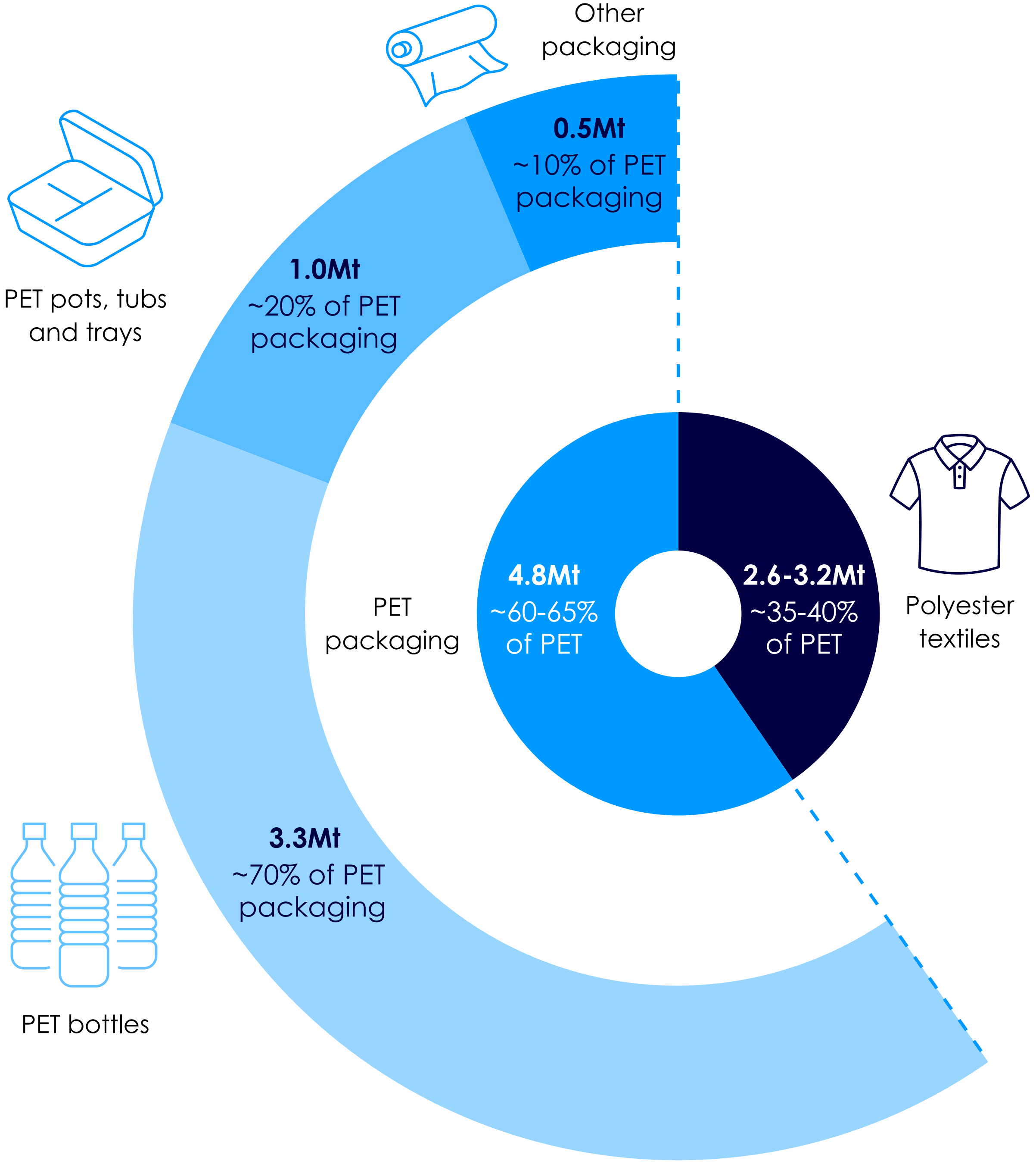
PET is used extensively in plastic packaging and synthetic textiles

- In Europe, PET is almost exclusively used in packaging (4.8Mt)[2] and textiles (2.6-3.2Mt)[e,1,2] and when used in textiles, it is known as polyester
- In packaging applications, PET is predominantly used for bottles (3.3Mt) or trays (1.0Mt)[2]
- 0.5Mt of PET is also used in other types of packaging, including PET as a film in monolayer and multilayer packaging, and in strapping[2]

European PET packaging and textiles consumption and product breakdown, 2020

Million tonnes

Total European PET consumption is estimated at ~7.4-8.0 million tonnes.



e Limited data is available on European consumption of both synthetic textiles and polyester textiles specifically (i.e., how much is put on the market, including imports). The data presented represents an estimate based on best available sources.

Exhibit 3

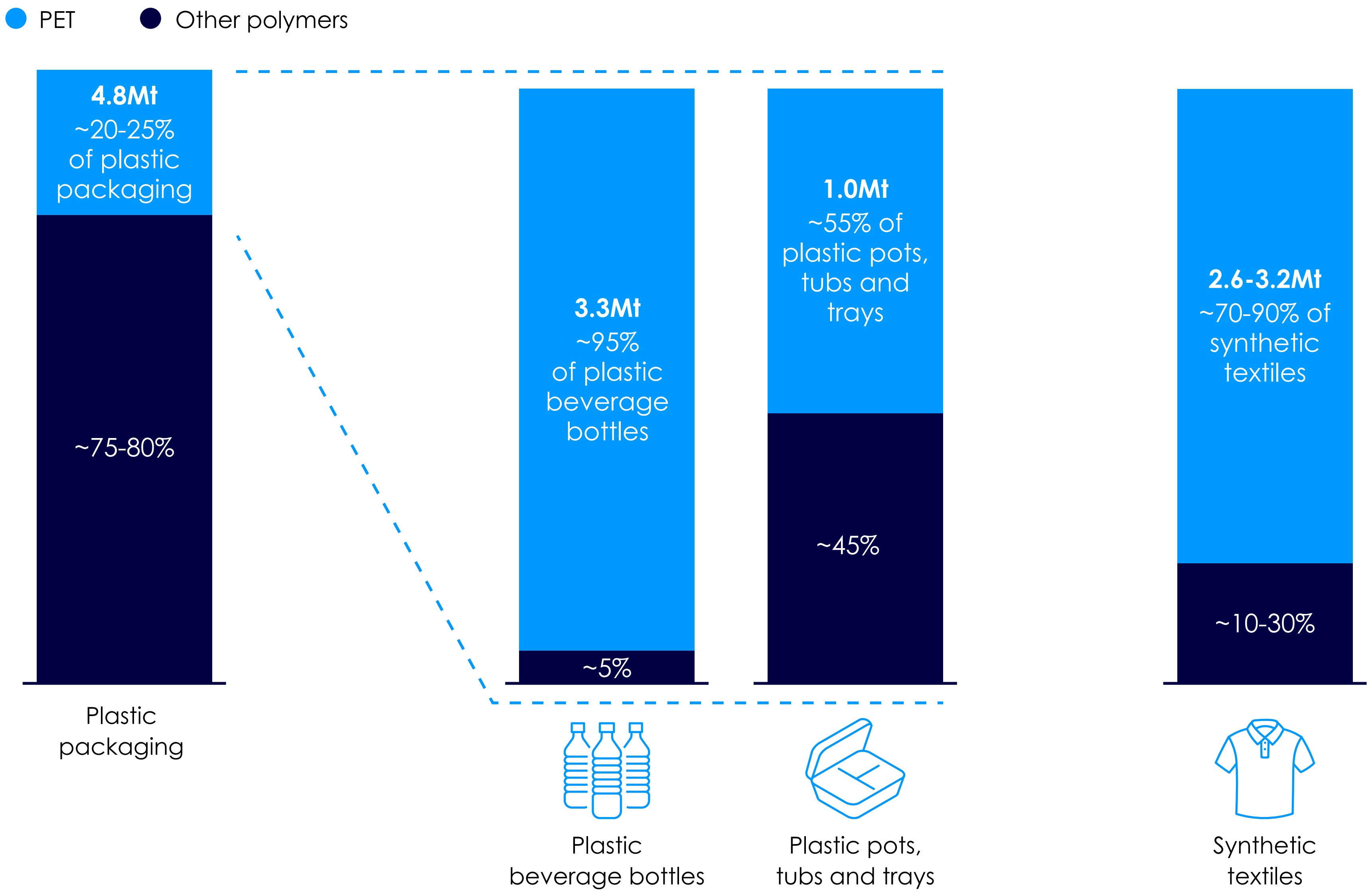
PET is the primary polymer used in plastic bottles, trays and synthetic textiles

- PET is one of the major plastic polymer types used in Europe alongside Polypropylene (PP) and Polyethylene (PE)[f,1,2] A circular solution for PET/polyester would be a significant step towards a circular packaging and textiles economy in Europe
- It is the primary polymer used in plastic beverage bottles, trays and synthetic textiles, making up ~95%, ~55% and ~70-90% of those markets respectively[2,3,21,22]. As a result of PETs' extensive use in bottles and trays, it makes up a quarter of the overall European plastic packaging market
- In addition to PET, PP is also widely used in trays[23] and Polyamide (also known as Nylon) is commonly used in synthetic textiles[24]

f Due to lack of available data, this figure combines EU packaging consumption data for PET with data on polymer demand from EU packaging converters. Converters take polymers and turn these into final products. Converter demand for PET in 2020 (used almost entirely in packaging) was 4.1Mt relative to PET packaging consumption of 4.8Mt. The difference may be accounted for by the balance of imports and exports of PET packaging as well as the demand for recycled PET.

PET share of European plastic packaging and textiles consumption, 2020

Million tonnes



0.5Mt of PET packaging are not displayed, corresponding to 'Other' packaging application.

1.2

Reduction, reuse, substitution and re-design

Examples of reduction, reuse, substitution and re-design of PET/polyester products are identified in Europe (Exhibit 4). Overall, the impacts have been meaningful but have not prevented the continued growth of PET/polyester usage in Europe.

These circular economy approaches have been driven by a combination of voluntary industry action, consumer behaviour changes and government policy changes.

Reduction:

Reduction of PET use in plastic bottles has been achieved through business model innovations (e.g., SodaStream home carbonation system to replace single-use bottles), down-gauging efforts by industry (reducing thickness of bottles) and through government action to reduce bottled water consumption (e.g., public water fountains and consumer behaviour campaigns to increase uptake of multi-use bottles). Reduction efforts have been less apparent and less successful in the apparel sector and overall consumption levels have grown[25].

Reuse:

Reuse rates for PET packaging are generally very low in Europe. However, reuse systems for PET bottles in Germany have been achieved through government policies in cooperation with industry, where they account for 15% of bottles in the water segment[4]. Reuse/resale of apparel in second-hand markets is a market-driven activity across Europe, as well as export of second-hand apparel to markets outside Europe. On average, 38% of the consumer household textiles placed on the market are collected separately when the consumer no longer wants them. 55% of this collected material is then redistributed as re-wearable textiles[5].

Substitution:

Shifting from PET to aluminium, glass or paper fibre-based materials for beverage containers and trays has happened in some market segments. In some cases concerns have been expressed about the actual contribution to environmental performance from these material substitutions[26]. Studies have shown that switching into PET for some applications can offer lower GHG emissions or higher recyclability for several non-plastic alternatives used at scale[27]. For example, switching from glass bottles into PET bottles can reduce the overall greenhouse gas emissions including manufacturing and transportation[27].

Re-design:

Widespread and long-standing voluntary industry efforts on design for recycling have been driven through collaborative platforms such as the European PET Bottle Platform, Petcore Europe, the Global Commitment to a New Plastics Economy (Ellen MacArthur Foundation) and the Consumer Goods Forum (e.g., phasing out problematic materials and additives as well as a shift from multilayers to monomaterials). Initiatives for textiles design (e.g., reducing PET/nylon blends) have been driven by not-for-profit initiatives, including the Ellen MacArthur Foundation and RISE.

Exhibit 4

Examples of PET reduction, reuse, substitution, re-design

Reduce

Venice Water Fountain Network[i]	• Installation of network of 126 fountains • Launch of fountain map and campaign to facilitate access • Limitation: Challenges to increase awareness and shift consumer patterns at scale	**Implemented** Italy

Reuse

Soda Stream[ii]	• Maker of at-home sparkling water machines to replace purchases of single-use soda bottles	**Scaled** International
Refillable bottle scheme[iii]	• Deposit scheme for PET refillable bottles within the mineral water sector • Make up 15% of market share[2] • Limitation: Requires collaboration with stakeholders across the value chain, particularly with retailers and distributors	**Scaled** Germany
ReCircle[iv]	• Reusable containers system for take-away operations in large area • Built in collaboration with network of take-away partners	**Implemented** Switzerland
Zero Waste Leeds[v]	• Interactive map with network of textile banks, charity shops, repair shops, sewing classes, clothes exchange sites • Aimed at reusing, repairing and upcycling clothes	**Implemented** UK

Substitute

Waitrose fiber-based ready meal trays[vi]	• Supermarket launches a ready meal range in fiber-based trays • Intended to provide a more sustainable alternative to black PET trays • Limitation: Measure should be implemented when environmental impacts (GHG) are proven beneficial against PET alternative	**Implemented** UK

Re-design

Sprite clear bottle[vii]	• Coca Cola shifted design to clear PET bottle from original green bottle (had been commercialised with that colour since 1961) • Coloured bottles have more limited future applications than clear bottles, once mechanically recycled	**Scaled** Europe

Sources: (i)venicetapwater.com; (ii)Soda Stream, https://sodastream.com/blogs/explore/fight-plastic (iii) Eunomia (2022) PET Market Europe; State of Play; (iv) recircle.ch; (v) zerowasteleeds.org.uk (vi) https://www.foodpackagingforum.org/news/fiber-tray-to-replace-black-plastic; (vii) https://www.cocacolaep.com/fj/news-and-insight/same-sprite-new-clear-bottle/.

ReShaping Plastics report p42 https://www.systemiq.earth/wp-content/uploads/2022/05/ReShapingPlastics-v2.1.pdf.

Critical raw materials study p17 https://www.systemiq.earth/wp-content/uploads/2022/11/Systemiq-2022.-Circular-Economy-CRM-Resilience-Summary-Presentation_final.pdf.

1.3 Recycling

Recycling rates for PET/polyester in Europe are highly variable depending on the product application and local systems and regulations.

Clear PET beverage bottles are recycled more than other PET product applications; with 50-55% recycling rates on average. These are driven by high collection and sorting of clear PET bottles, which constitute 72% of sorted PET bottles in Europe[4] and are suitable for the production of transparent packaging material (remaining volumes are made up of 27% colored bottles[4] and 1% opaque bottles[4] which are only suited for darker colored and lower grade rPET applications with reduced value[2]). Recycling rates vary significantly, primarily based on whether a well-functioning bottle return scheme is in place[4,8]. Recycling rates are significantly lower for PET trays and textiles (Exhibit 5).

Across Europe, three-quarters of all PET/polyester is not recycled and goes to landfill, incineration with energy recovery or littering after one use. As of 2020, only 17% of bottles (by weight) are recycled back into another bottle, with most bottle recycling going into textiles and trays (Exhibit 6-7).

Data on recycling rates for trays and textiles is limited; however, this is expected to be significantly below available-for-recycling rates of 20% and 10% respectively. Polyester recycling includes open-loop recycling applications such as insulation materials or mattress fillings and small share – likely less than 1% – recycled back into textiles[5,28,29].

PET packaging is the subject of concerted policy action to encourage higher recycling rates, as well as voluntary commitments from consumer brands (fashion and beverage companies) pledging to use more recycled PET in their textiles and packaging. Meeting these policy targets and industry demands will require a rapid scale-up of supplies of high-quality recycled PET (Exhibit 7).

In parallel, European policies are evolving rapidly to encourage circular economy approaches for plastic packaging and textiles. This is expected to further increase the pressure for scale-up of PET/polyester reuse and recycling, and to provide supportive measures such as eco-design requirements, separate collection of packaging and textiles and financing from extended producer responsibility schemes (Exhibit 8).

However, increasing PET/polyester recycling rates to meet demand is not straightforward. Mechanical recycling faces limitations on product quality[30,31].

Mechanical recycling challenges include:

1. Mixing various polymer types and grades from different product applications or multi-material formats
2. Degradation of polymer chains during recycling process and,
3. Contamination with other products (e.g., oils)

PET is advantaged in the sense that some of those mechanical recycling challenges can be overcome more easily than, for example, the mechanical recycling of polyolefins, although it leads to additional cost. For example, the development of dedicated bottle collection systems (e.g., deposit return systems) combined with uniform PET bottle grades helps to reduce the loss of physical properties and post-recycling treatments are available for mechanically recycled rPET (solid state post-condensation) to help restore the physical properties of the material.

Across Europe, three-quarters of all PET/polyester is not recycled.

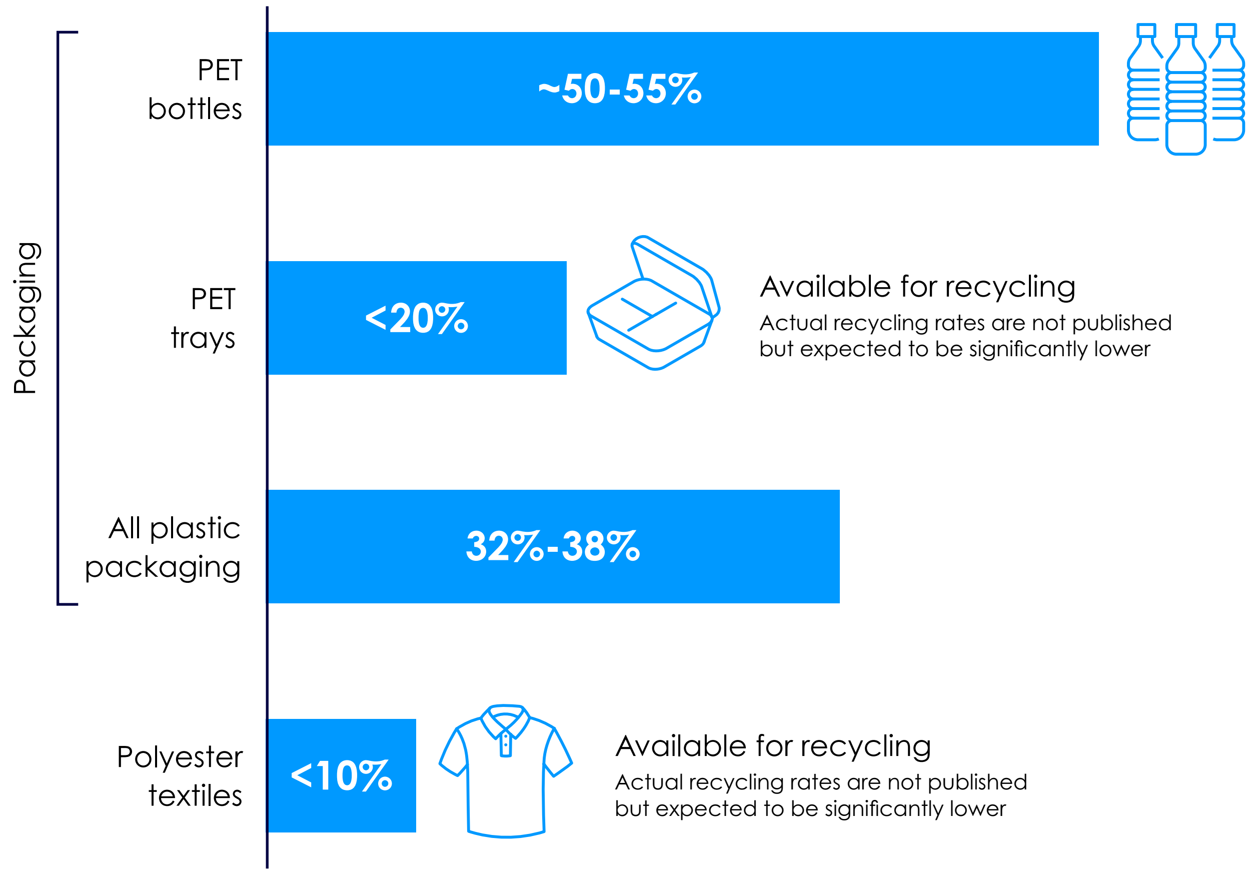
In each recycling loop, two-thirds of all recycled PET / polyester is converted from a contact-sensitive application (beverage bottles) to a non-contact sensitive application with a low likelihood of being recycled again.

Exhibit 5

PET bottle recycling rates are comparatively high, yet trays and textiles fall well behind

- In 2020, compared to the overall weight of products placed on the market, the average European rate for recycling of all post-consumer plastic packaging waste was 32%-38%[6,7], with a range of 10% to 57% in different countries[6]
- For PET bottles specifically, the recycling rate is 50-55%; for trays, this is below 20%[4]. Recycling rates are estimated to be below 10% for polyester textiles, although data is not readily available
- PET bottles' higher recycling rates are facilitated by numerous factors, including widespread collection and sorting of bottles for recycling, along with adoption of Deposit Return Schemes (DRS) in some European countries, such as Norway and Germany.[9] Collection for recycling rates of PET bottles vary across Europe, with countries like Germany, Finland and Lithuania reporting rates above 90%, while others like Bulgaria, Greece, Portugal and Spain have rates below 40%[4]
- The market for PET tray recycling is evolving. Today's low mechanical recycling performance of PET trays relative to PET bottles is determined by several factors:
  - Lack of widespread separate collection systems for trays[4]
  - Lack of proper sorting facilities capable of separating PET trays from other waste packaging formats[4]
  - Presence of multi-materials, multilayers, adhesives, and films leading to contamination (particularly light material fractions such as lidding films)[4,32]
  - Brittleness of the PET used to manufacture trays which results in higher fines production and can impact rPET quality and yield, including when trays are recycled together with bottles[4]

European average recycling rates, 2020



Notes: Data refers to mechanically recycled volumes. The recycling rate of beverage bottles is quoted as 50%, where this is calculated based upon rPET output as a proportion of the total weight of bottles placed on the market, including the weight of non-PET parts such as caps, lids and labels. However, when discounting for these non-PET parts, the recycling rate of PET only is 55%.

Data is not available for recycling rates of PET trays and polyester. However, it is widely understood that recycling rates are very low, and significantly below collection rates, which are shown in the chart.

Data is not available for recycling rates of Polyester. Available data estimates 32%[5] waste volumes from apparel and household textiles are directed to separate streams. From this, 26%-30%[5,28] are destined for recycling (these estimates consider downcycling of textiles waste into shoddy applications like insulation or mattress filling), consolidating an approximate 8-10% recycling rate. Other polyester products are assumed to have lower recycling rates. Numbers do not account resale or reuse of wearable textiles.

Eurostat has calculated a European plastic packaging recycling rate of 38%[6] and PlasticsEurope of 32% (The Circular Economy for Plastics, 2022, PlasticsEurope). Those two numbers are calculated with the new calculation rules (input to recycling facilities excluding preparation steps such as sorting, shredding and washing as required by the new 2019/665 or 2019/1004). Subsequent reports are estimating a much lower recycling rate in Europe in 2020: 15-17% arguing that a larger proportion of plastic waste is generated than countries are reporting, and which is disclosed by Eurostat. Source: Reshaping Plastics, Systemiq, 2022, and Europe's Missing Plastics, Materials Economics, 2022.

Source: (1) Systemiq, Reshaping Plastics, (2) PET Market: State of Play 2022, Eunomia (2022), (3) Eurostat, (4) Sorting for Circularity, Circle Economy & Fashion for Good, (5) Demand, Consumption, Reuse and Recycling of Clothing and Textiles in Germany, Federal Association for Secondary Raw Materials and Waste Management (2020), (6) Eunomia & Zero Waste Europe, How Circular is PET?.

Exhibit 6 (see next page)

A PET/polyester flow map for Europe illustrates low circularity and a dependence on PET bottles as recycling feedstock

- As of 2020, the overall PET/polyester recycling rate was around 25%, with 75% of PET/polyester going to landfill, incineration or littering
- Recycled PET is used in multiple products. Of bottles that are recycled, 30% are recycled back into other bottles, whilst 31% flows to trays, 13% to other packaging and 26% to textiles[2]
- Key issues of the current system include:
  - Mechanical recycling technology cannot recycle all non-bottle PET products
  - Lack of dedicated collection schemes (e.g., textiles)
  - Unharmonised collection systems (e.g., for bottles)
  - Lack of sorting processes (e.g., for trays and textiles)[2]
  - Losses during the sorting and recycling processes
  - Variation in feedstock quality (e.g., contaminants from foods and other polymers)
  - Insufficient design for recycling

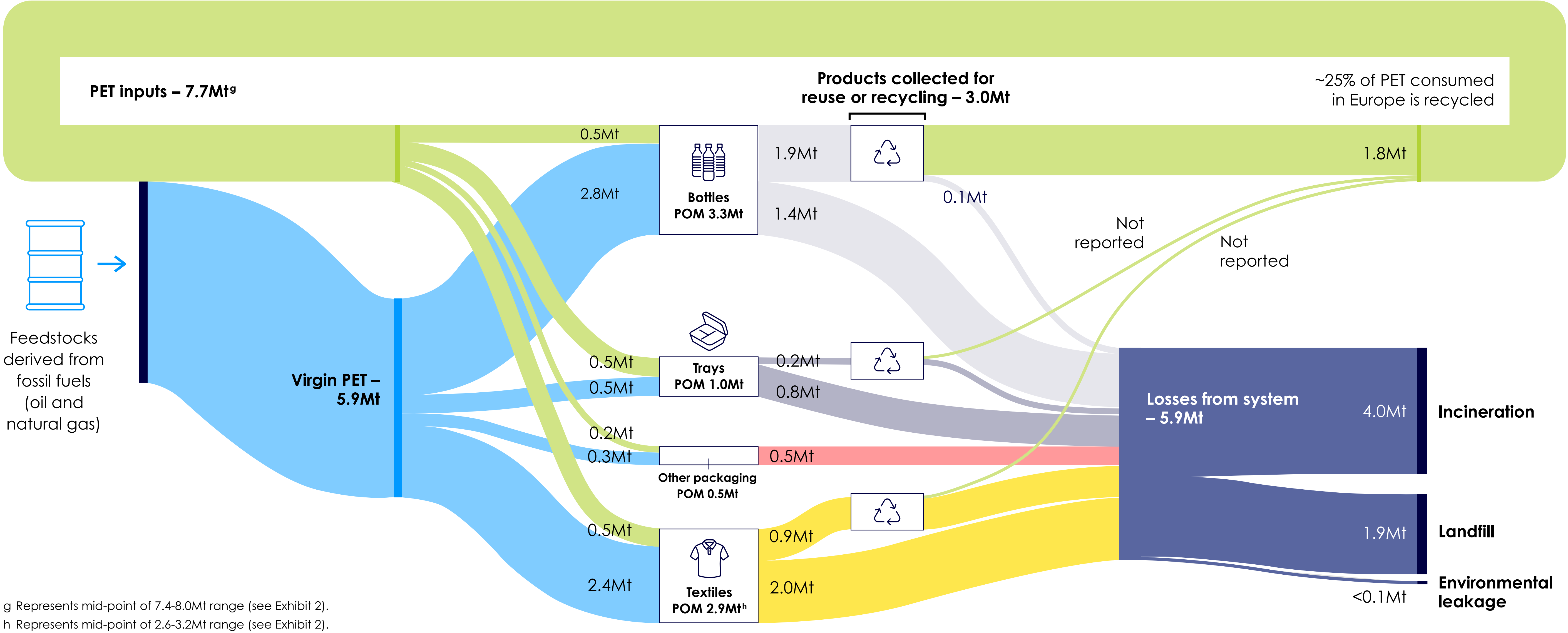
Notes: bioPET is not shown due to low volume. Global production was 0.15Mt in 2021 Bioplastics Market data, European Bioplastics (2021). Additionally, this chart does not illustrate flow of PET/polyester outside the geographical boundary of Europe and does not provide a quantified estimate for contribution of trays or textiles to rPET supplies, because of data gaps. As illustrated on previous pages, reuse of some products is happening in Europe (e.g., textiles and PET water bottles in Germany), this is not shown on the material flow diagram to reduce complexity.

Exhibit created through adaptations of data from: How circular is PET?, Eunomia and Zero Waste Europe (2022), PET Market: State of Play 2022, Eunomia (2022), and Plastic in textiles: towards a circular economy for synthetic textiles in Europe – European Environment Agency (2021) and Environmental and Socioeconomic Impacts of Polyethylene terephthalate (PET) Packaging Management Strategies in the EU, A. Bassi et. Al (2022); Note: where possible, this diagram excludes weight of non-PET parts, such as bottle caps, lids and labels.

European PET flows, 2020

Million tonnes

Virgin PET · Recycled PET (rPET) · **POM** – Put On Market · **Trays** – Refers to Pots, Tubs and Trays · Product collected for reuse or recycling



g Represents mid-point of 7.4-8.0Mt range (see Exhibit 2).
h Represents mid-point of 2.6-3.2Mt range (see Exhibit 2).

Exhibit 7

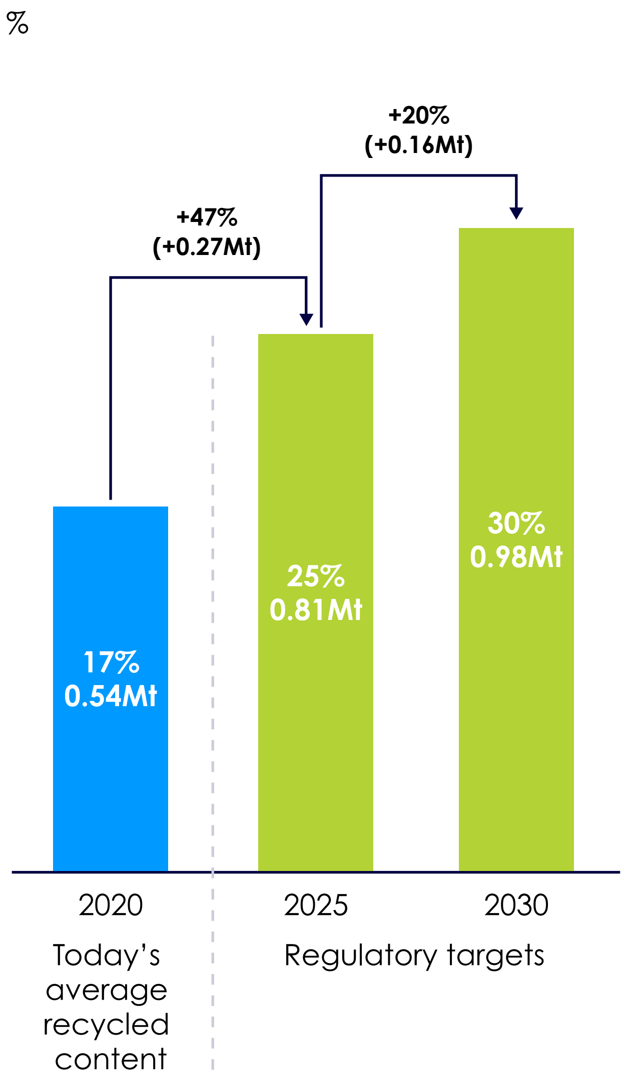
Demand for high-quality and contact-sensitive recycled PET will continue to grow

Demand growth will be driven by:

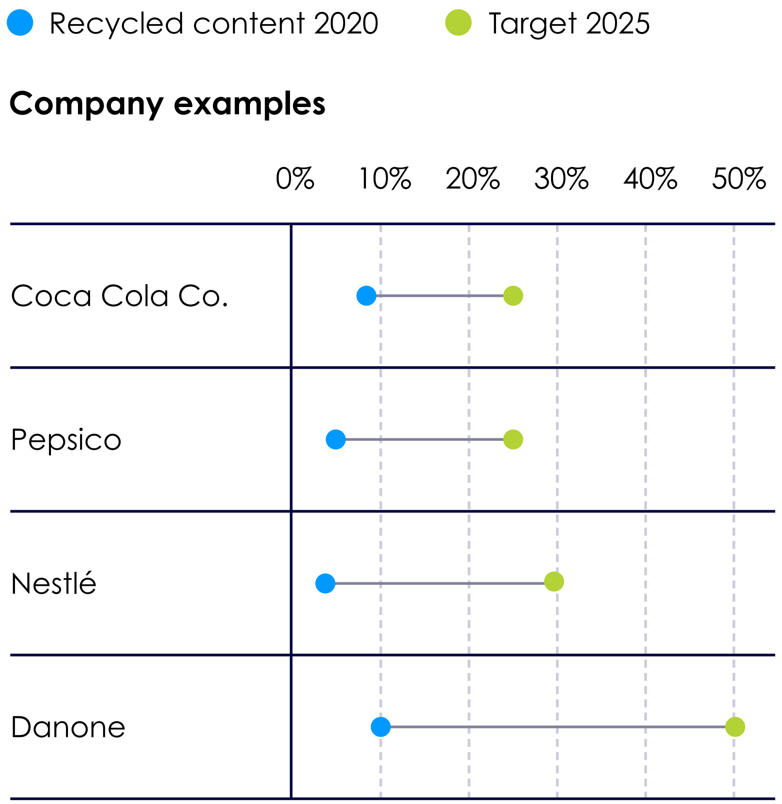
- Policy changes at EU level: the Single-Use Plastics (SUP) Directive sets average recycled content in PET beverage bottles of 25% by 2025 and 30% by 2030. This implies a particularly steep near-term increase in demand by at least ~50% from 2020-25[10], which, based on historical growth in the sector, will be a challenging target to meet[21]
- Industry voluntary commitments to even higher rPET content in their products (packaging and textiles) – e.g., from signatories to the Global Commitment to a New Plastics Economy led by the Ellen MacArthur Foundation[2]

Notes: Brands listed in exhibit represent companies with high use of PET as a share of total packaging materials.

Recycled content in beverage bottles – Single-Use Plastics (SUP) Directive[1]



Global brand commitments on recycled content for packaging[2]



The Coca-Cola Company, Pepsico and Nestle commitments apply to global plastic packaging.
Danone commitment applies for for all beverage bottles.

Exhibit 8

European policies are evolving rapidly to encourage circular economy approaches for plastic packaging and textiles

Relevant European Commission policies	**Timeline** for next revision or implementation step (estimated or expected)	Potential relevance of policy to PET/polyester circularity
EU strategy for Circular and Sustainable Textiles	Published in March 2022	• Strategy document including proposed measures proposed to increase reuse and recycling rates for textiles
EU communication on making sustainable products the norm	Published in March 2022	• Digital Product Passports based on mandatory information requirements on circularity and other key environmental aspects including textiles and packaging
Regulation on recycled plastic materials and articles intended to come into contact with foods	Adopted in September 2022	• Regulation establishing requirement plastic recycling processes which output materials are intended to come into contact with foods. It includes PET as a material and the requirements that apply to specific PET recycling processes are identified separately
Single-Use Plastics Directive (SUPD)	Took effect July 2021	• PET beverage bottles are specifically identified for minimum recycled content targets for beverage bottles (25% by 2025 and 30% by 2030)
Single-Use Plastics Directive (SUPD) Implementing Act	Adoption expected for Q1 2023	• Implementing act to provide further technical guidance on the targets set in SUPD
Packaging and Packaging Waste Regulation (PPWR)	Draft legislation published in November 2022 | Adoption expected for middle 2023	• Reuse targets for beverage bottles and packaging in general • Design for recycling targets for beverage bottles and packaging in general • Increased use of deposit return schemes for beverage bottles across Europe • Recycled content for beverage bottles, contact sensitive packaging in general • Indication on the recognition of chemical recycling as a process to counts toward recycling targets and recycled content targets
Revision of the Waste Framework Directive (WFD)	Draft legislation expected in Q2 2023	• Harmonised EU rules on extended producer responsibility for packaging and textiles, and economic incentives to encourage design for recycling ("eco-modulation of fees")
Regulation on Ecodesign for Sustainable Products	Draft legislation published in March 2022 | Adoption expected for middle 2023	• Mandatory minimums for the inclusion of recycled fibres in textiles, making them longer lasting and easier to repair and recycle • Ban on destruction of unsold products under certain conditions, including unsold or returned textiles
Revision of the Waste Shipment Directive	Draft legislation published in November 2021 | Adoption expected for Q2 2023	• May only allow the export of textile waste to non-OECD countries under certain conditions • Development of specific EU-level criteria to distinguish waste properly and increase transparency and sustainability in global trade in textile waste and used textiles

New developments

for PET/polyester recycling

There is growing attention on the potential for chemical recycling technologies to increase plastic recycling rates in Europe, alongside mechanical recycling and reuse.

Chemical recycling comprises three or four main sets of technologies (Exhibit 10), which each have significant differences: (1) depolymerisation, (2) pyrolysis, (3) gasification and (4) solvent-based recycling is sometimes classified as a type of chemical recycling[i,33,34].

As noted earlier, the chemical composition of PET/polyester means that it is particularly suited to a type of chemical recycling known as 'depolymerisation'. Depolymerisation includes methanolysis, glycolysis and hydrolysis technologies that break down PET/polyester waste into its chemical precursors, called monomers. Monomers are re-polymerised back into contact-sensitive ('food-grade') recycled plastics with the same functional properties as virgin plastic[j] (Exhibit 9). Depolymerisation is suitable for those PET/polyester feedstocks that have lower recycling rates today, including coloured bottles, trays, high polyester content textiles, and waste PET from the mechanical recycling process (Exhibit 11).

Chemical recycling of plastics is a prominent topic in Europe. Stakeholders are concerned about negative environmental impacts (particularly GHG emissions), competition with mechanical recycling, and the viability of mass-balancing methodologies for mixing of virgin and recycled feedstocks. These debates have primarily focused on thermal conversion technologies, such as pyrolysis, which are typically applied to polyethylene or polypropylene plastics and not suitable for PET/polyester. PET/polyester depolymerisation is generally considered to be less energy intensive than pyrolysis. Unlike pyrolysis, PET/polyester depolymerisation may not necessarily require mass-balancing, because it can produce one single set of chemical outputs which can then be used and tracked without further mixing with other substances in subsequent polymerisation steps. Although on a case-by-case basis, and based on existing logistics and infrastructure (e.g., size and interconnection with other processes) mass balancing may be favoured[k].

Chemical recycling of PET/polyester is a small-scale technology in Europe today; however, industrial scale facilities have been announced for construction (Exhibit 13) and chemical recycling solutions are central to recently announced European value chain collaborations on textile-to-textile recycling[l].

i Solvent-based recycling does not change the chemical structure of the polymer itself. As such, it has been argued that it should be seen as mechanical rather than chemical recycling. The European Commission 2019 report's terminology uses the logic that since chemicals are used in solvent-based purification to change the formulation of the plastic, it can be described as chemical recycling.

j Legality of contact-sensitive use of plastics from chemical recycling depends on the specific application of the technology and may not apply to all types of PET depolymerisation. In Europe, it is subject to Regulation (EU) No 10/2011 and Regulation (EU) 2022/1616 Commission Regulation (EU) 2022/1616 which states that the manufacture of plastic materials and articles with substances obtained at a high level of purity from waste materials, and that are included in the Union list established by Regulation (EU) No 10/2011, or subject to certain derogations, should be subject to that Regulation and excluded from 2022/1616. Whereas other substances in which incidental contaminants cannot be assumed a priori to be absent or easily excluded, including mixtures, oligomers, and polymers produced from waste, should be subject to 2022/1616. Note that all of those technologies can be used to produce chemical precursors called monomers. Some technology providers may decide to use those technologies to produce oligomers. However, in this case, the mixture produce may not be compliant with the food safety regulations mentioned above and the presence of oligomers may exclude them from regulation 2022/1616.

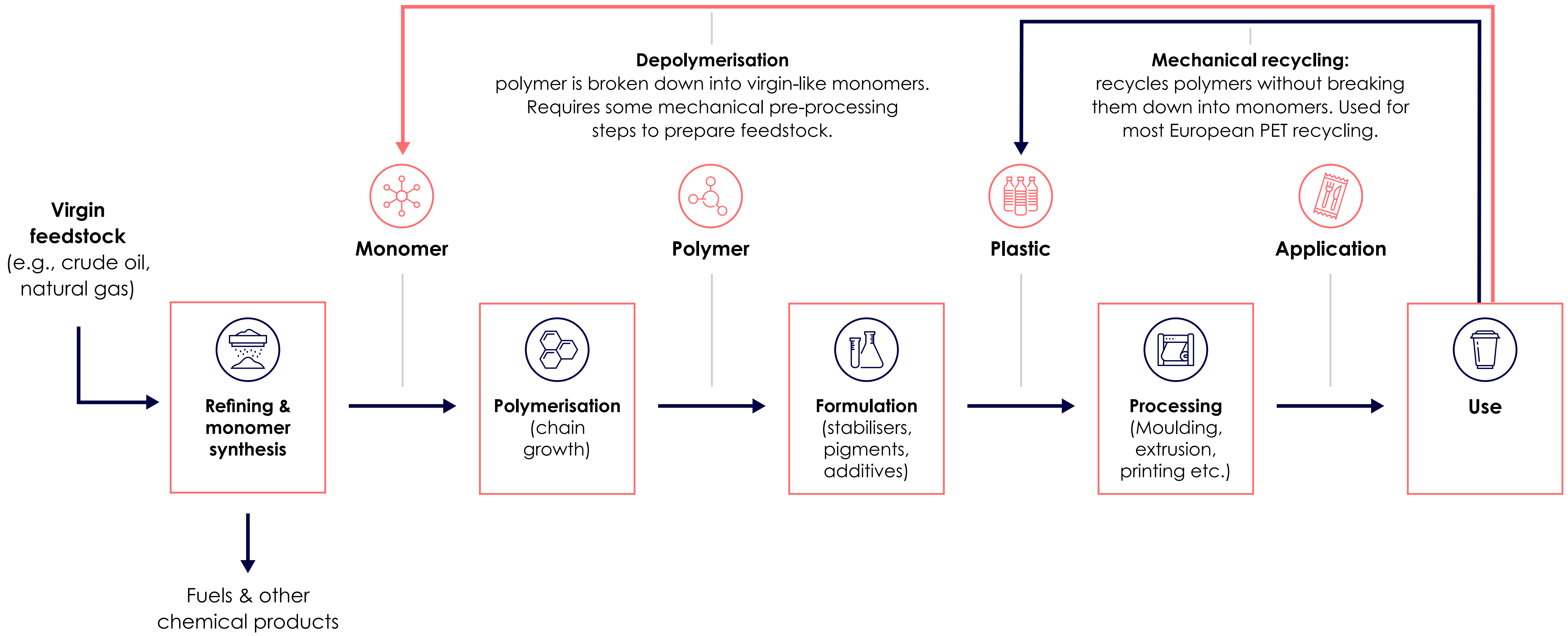
k In contrast, chemical recycling via pyrolysis relies on mass balancing because cracker facilities used for manufacturing of polyethylene or polypropylene plastics are too large for exclusive use of recycled feedstocks and produce multiple outputs including fuels and chemical precursors which may not be used for plastic production.

l Examples: Fashion For Good polyester recycling initiative involves CuRe Technology, Garbo, gr3n and PerPETual; T-Rex textile recycling initiative involves Infinited Fiber Company, BASF, and CuRe Technology; Whitecycle textile recycling project convened by Michelin involves Carbios.

Exhibit 9

Overview of PET production and recycling processes, showing both mechanical and depolymerisation recycling pathways

Current PET recycling rates are being achieved through mechanical recycling. PET can also be recycled via molecular methods such as depolymerisation.



Notes: Both depolymerisation and mechanical recycling require preprocessing steps and so will both benefit from design for recycling measures. Exhibit adapted from De Smet, M. & Linder, M. (Eds.), A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions, European Commission, Brussels, Belgium (2019).

Exhibit 10

There are three types of PET depolymerisation

"Chemical recycling" captures a range of technologies, not all of which are applicable to PET, and which have significant differences

Pyrolysis is not applicable to PET/polyester

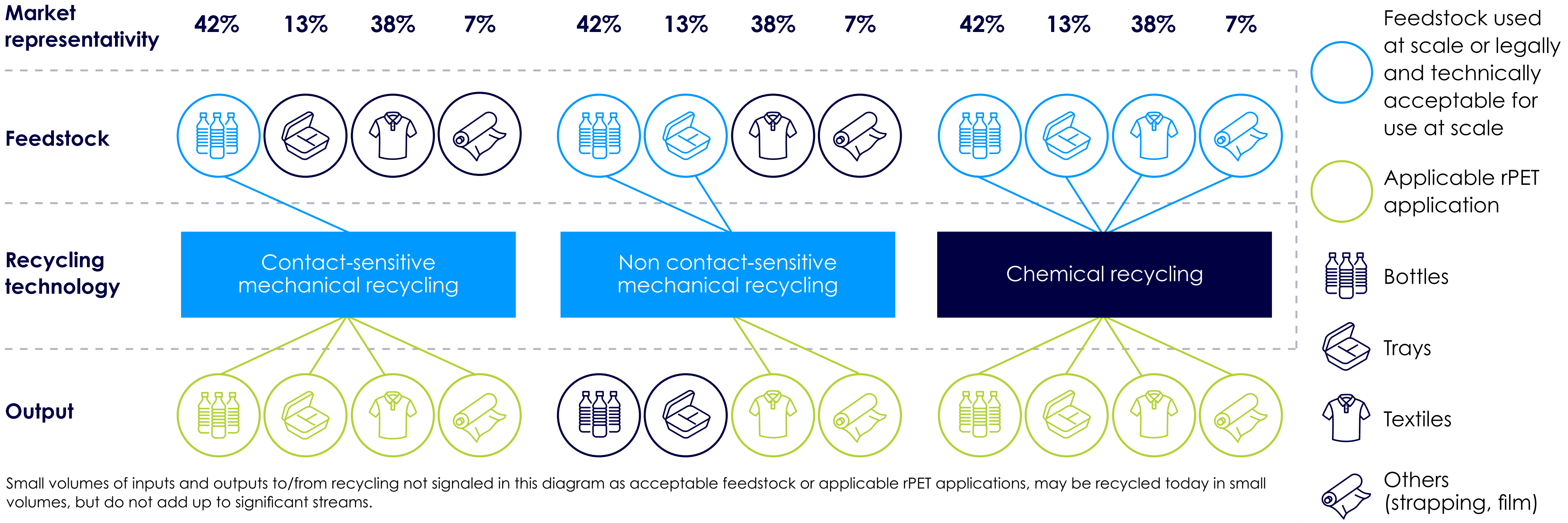
	Mechanical	Chemical recycling				
		Depolymerisation			Thermal conversion	
Recycling method	Recycling technologies remould plastics into new applications without changing their chemical composition	Recycling technologies that break plastic polymers down into smaller molecules (monomers or oligomers) that are reconstituted back into plastics with the same properties as new plastics			Recycling technologies that break down the polymer chain into hydrocarbon products that can be used in plastic-to-plastic supply chains (e.g., naphtha, methanol)	
Sub-types + descriptions		**Methanolysis** Polyester renewal technology using methanol as a reagent to break down PET	**Hydrolysis** Polyester renewal technology using water as a reagent to break down PET	**Glycolysis** Polyester renewal technology using ethylene glycol as a reagent to break down PET	**Pyrolysis**[1] (not for PET) Break down of polymer by heating within inert atmosphere	**Gasification** Break down of polymer by heating alongside steam/air
Examples of companies in Europe	Faerch Indorama	Eastman Loop Industries	Carbios Gr3n	Axens Ioniqa	Plastic Energy Mura Technology	Enerkem

Note: Players listed as examples may have facilities located outside of the EU and plan to increase EU capacity in a near future.

Exhibit 11

Chemical recycling can process some hard-to-recycle products into virgin-equivalent PET, suitable for contact-sensitive applications

- Clear and light-blue bottles can be mechanically recycled back into similar-coloured PET products[4,m]. Production of contact-sensitive rPET from mechanical recycling of beverage bottles is permitted by EFSA if other non-food grade inputs to the recycling process contained in feedstock do not exceed 5%[n].
- Mixed-colour PET cannot be recycled into lighter-colour applications but can find new application in same colour or darker-coloured applications[4].
- PET trays can be recycled back into PET trays. However, several barriers are limiting this: (i) brittleness of the PET used to manufacture trays results in significant fines production, limited yield, and limits to processability; (ii) limited collection and sorting facilities for this product causes limitations in feedstock[4]; (iii) EFSA approval for contact-sensitive use of rPET derived from trays, and more stringent rules recently released on the use of non-approved rPET behind a functional barrier layer.
- Chemical recycling can process some PET/polyester applications that are hard to mechanically recycle, generating virgin-quality contact-sensitive rPET outputs that maintain high economic value[34]. Textiles could transition from a relevant recycled output application, currently taking up to 26% of mechanically recycled PET[2], to becoming a stream of feedstock for the production of virgin-like recycled PET that can be used in any application.
- More transparency is needed on additional feedstock constraints that may appear as chemical recycling technologies are deployed and scaled, potentially increasing costs to feed chemical recycling plants.



Small volumes of inputs and outputs to/from recycling not signaled in this diagram as acceptable feedstock or applicable rPET applications, may be recycled today in small volumes, but do not add up to significant streams.

Note: Exhibit adapted from Closed Loop Partners, 'Transition to a Circular System for Plastics' to PET applications.

m The wide variety of pigments used in the market today means that mechanical recycling of coloured bottles into clear or light coloured applications is not happening at scale (with the exception of light blue bottles) however technologies exist to mechanically recycle coloured bottles into coloured bottles.

n European Commission directives.

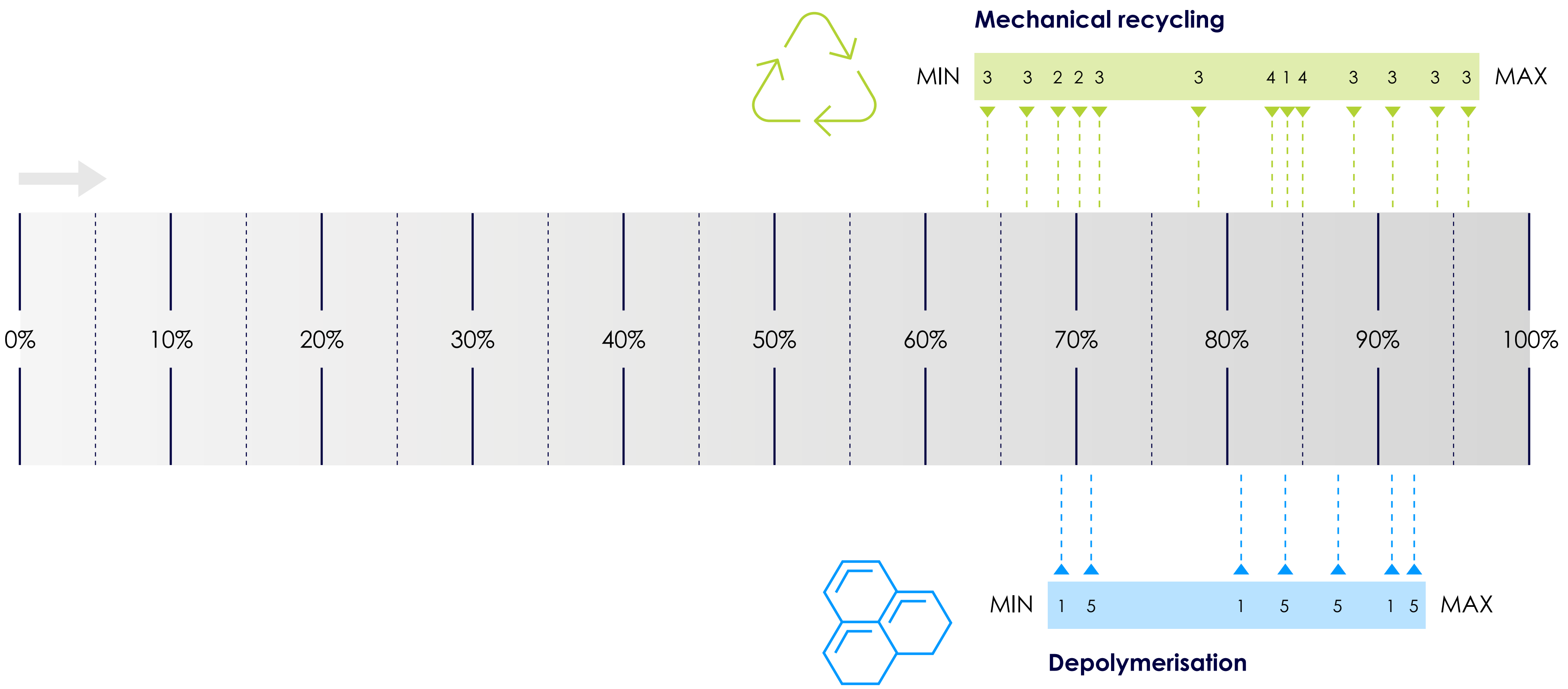
Exhibit 12

Depolymerisation and mechanical recycling of PET achieve similar yields

- Material-to-material yields of depolymerisation are generally similar to mechanical recycling yields
- Yield ranges are based on consolidated averages of diverse technologies and are not specific to contact-sensitive recycling methods. For both mechanical and chemical recycling, process yields are dependent on feedstock quality
- More specific, granular and comparable information on material-to-material yields is not available in published research for example specifying type of feedstock and type of recycled plastic that is produced (e.g., contact-sensitive or not)

Range of PET material-to-material yield per treatment of recycled plastics

2 3 References. Each reference is reporting more than one data point. Each individual data point has been reported separately.



Note: Yield obtained from 1,000 kg of waste plastic together with additives prior to entry into recycling facility (includes in-facility pre-sorting, washing and extrusion steps). Pre-sorting yields have been applied to depolymerisation yields reports by reference (5) according to reference (1).

(1) Closed Loop Partners, Transition to a Circular System for Plastic, 2021, (2) G. Loncaa, et al., Assessing scaling effects of circular economy strategies: A case study on plastic bottle closed-loop recycling in the USA PET market, 2020 (3) I. Antonopoulos et al., Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers, 2021 (4) Systemiq, Achieving Circularity in Norway, 2021 (5) Eunomia, State of Play: Chemical Recycling, 2020.

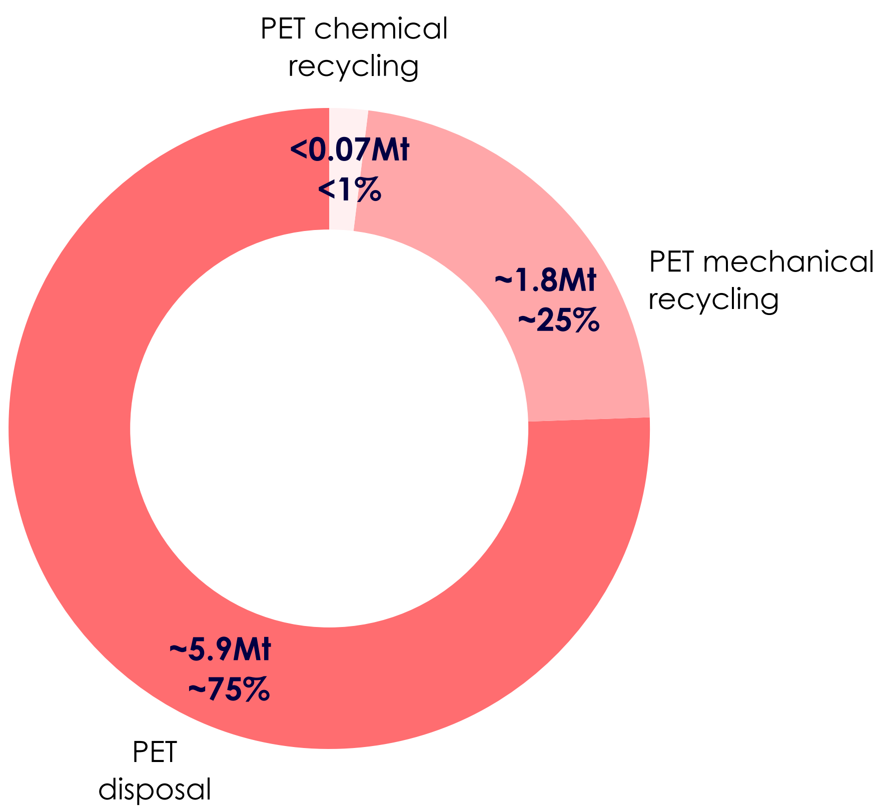
Exhibit 13

Significant PET depolymerisation commitments have been recently announced

- Installed European chemical recycling (depolymerisation) capacity for PET/polyester is currently 0.07Mt per year[4], equivalent to less than 1% of PET/polyester used in Europe
- Large industrial-scale PET depolymerisation facilities have recently been announced in Europe° and would cover an additional 5% of PET/polyester used in Europe, including:
  - Eastman facility in France, to process 160,000 tonnes per year[15]
  - Carbios / Indorama Ventures facility in France, to process 50,000 tonnes per year[18]
  - Infinite Loop / Group Suez facility in France to process 70,000 tonnes per year[17]
  - Axens / Toray Films Europe facility in France to process 80,000 tonnes per year[16]
  - Ioniqa upcoming facilities in the Netherlands to process 10,000 tonnes per year[19]

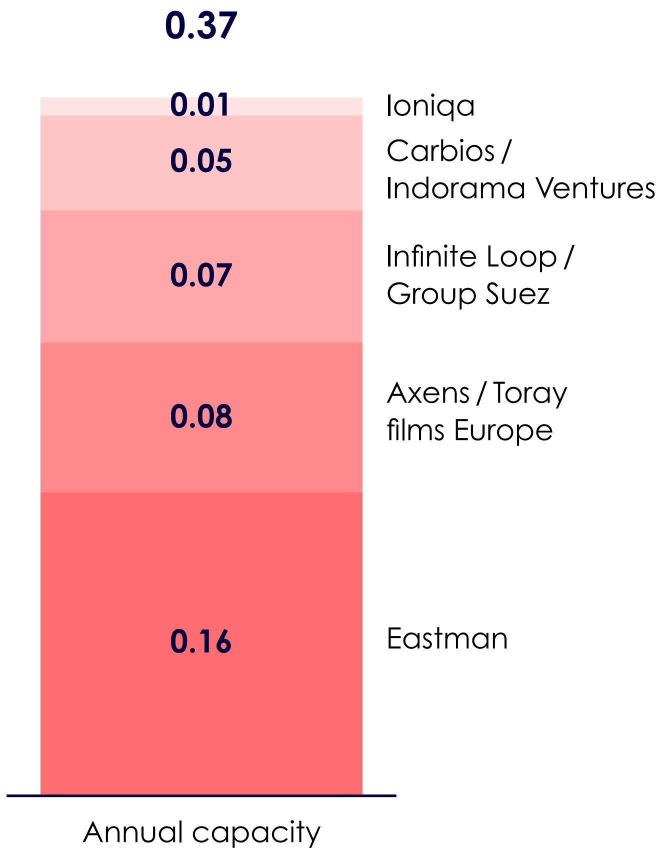
Annual European PET after-use destination by technology type, 2020

Million tonnes/year
% share of PET/polyester used in Europe



Announced capacity for future installations of chemical PET recycling technologies in Europe

Million tonnes/year



Note: PET depolymerisation represents capacity rather than utilisation.
Source: (1) PET Market: State of Play 2022, Eunomia (2022), and (2) How circular is PET?, Eunomia and Zero Waste Europe (2022).
o Based on publicly available information, it is unknown if projects from technologies providers have final investment approval.

Research insights

for complementary circular economy approaches in the PET/polyester system

Published studies provide insights to guide industry and policy-makers on the complementary application of different circular economy approaches (reduction, reuse, substitution, re-design, mechanical and chemical recycling) to reduce plastic waste, reduce dependence on fossil-fuel-based feedstocks, increase resource efficiency, and lower greenhouse gas emissions.

Complementarity can be guided by research insights on the relative negative environmental impacts from different circular economy approaches, particularly in terms of GHG emissions, plastic waste generation and primary fossil-fuel resource demand. Feedstock suitability, economic factors and market demand are also relevant to a complementarity assessment.

There is no published system model for the PET/polyester system that allows for a system-level assessment of the environmental impacts from different scenarios for complementary application of different circular economy approaches. Knowledge gaps and uncertainties in the PET/polyester system impede complementarity assessments and therefore modelling and scenario assessment tools should be designed with sensitivity assessment for key modelling parameters and input assumptions.

There is no published system model for the PET/polyester system that allows for a system-level assessment of the environmental impacts from different scenarios.

3.1

Reduction, reuse, substitution and re-design

Multiple studies indicate that positive environmental and socio-economic benefits can be achieved through reduction of avoidable PET/polyester, shifting from single-use to reuse models (in some cases) and shifting material choices into lower-impact alternatives (including both switches into PET/polyester from higher-impact materials or out of PET/polyester into other materials).

Studies highlight the need for significant application of reduction and reuse strategies across the plastics system in order to stay within the carbon budget required for alignment with the Paris Agreement[p].

The benefits and limitations of reduction, reuse and substitution approaches are highly dependent on the product application in question (Exhibit 14). Evidence is lacking on the overall size of the reduction, reuse and substitution opportunity away from PET/polyester, and the potential for substitution into PET/polyester from other materials, where this would be environmentally beneficial.

Studies and industry guidance agree that design for recycling (for both packaging and textiles) is needed to unlock the full potential of both mechanical recycling and PET/polyester depolymerisation.

p Eunomia & Zero Waste Europe (2022) – Is Net Zero Enough for the Material Production Sector. Estimates suggest that plastic demand would need to reduce by 3% each year, halving annual consumption by 2050 and reducing per capita consumption by 75%.

Exhibit 14 (also see next page)

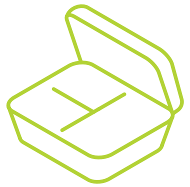
Reduction, reuse and substitution approaches are essential and their application is highly dependent on the product in question. In addition, re-design is needed on the PET/polyester that remains to unlock the full potential of recycling

Product/ application	Lever	Potential applications	Limitations
Bottles 	**Reduce**	Plastic use for bottles can be reduced through lightweighting or shifts in consumer behaviour	Challenges to change consumer behaviour at scale
	Reuse	Bottles are amongst top plastic applications with greatest potential for shifts towards reuse and new delivery methods[ii,iii] PET materials can be suitable for reusable containers or bottles, which could then also be recycled once unsuitable for further reuse	Infrastructure development and consumer behaviour change; assessing impacts of reuse logistics and infrastructure
	Substitute	Materials are available for substitution (e.g., glass, aluminium, paper)	Low applicability in some cases, due to potential GHG and cost impacts of alternative materials[i,27]
	Re-design	Move from coloured or opaque to transparent/uncoloured bottles and ensure sleeve/label and adhesive is not problematic for recycling[vii]	In a minority of cases coloured or opaque bottles are required to protect light-sensitive liquids

Exhibit continues on next page

Sources: (i) Systemiq, Breaking the Plastic Wave; (ii) Systemiq, Reshaping Plastics; (iii) Ellen MacArthur Foundation, Catalysing action, 2017; (iv) McKinsey and GFA, Fashion on Climate; (v) Zero Waste Europe. Reusable vs Single-Use Packaging; (vi) Ellen MacArthur Foundation, The New Plastics Economy; (vii) Consumer Goods Forum Golden Design Rules (2021) www.theconsumergoodsforum.com/environmental-sustainability/plastic-waste/key-projects/packaging-design/; (viii) Sorting for Circularity Europe, Fashion For Good (2022) https://reports.fashionforgood.com/report/sorting-for-circularity-europe/

Exhibit 14 (continued)

Product/ application	Lever	Potential applications	Limitations
Trays 	**Reduce**	Plastic use for trays can be reduced through lightweighting or shifts in consumer behaviour, or reducing unnecessary packaging	Challenges to change consumer behaviour at scale
	Reuse	Food services applications have high potential for shifts towards reuse and new delivery methods[i, iii] PET materials can be suitable for reusable containers or bottles, which could then also be recycled once unsuitable for further reuse	Infrastructure development and consumer behaviour change; assessing impacts of reuse logistics and infrastructure
	Substitute	Materials are available for substitution (e.g., paper fibre-based)	Case-by-case assessment of potential GHG and cost impacts of alternative materials, as well as recyclability and impact on food preservation
	Re-design	For all PET trays - eliminate use of undetectable carbon black and use transparent and uncoloured PET; switch to mono-material PET where possible; ensure labels, adhesives, printing and lidding films are not problematic for recycling[vii]	In some cases coloured pigments are used to enable use of recycled PET that retains original pigmentation
Textiles 	**Reduce**	Reduce significant wastage of unsold apparel stock, e.g., through stock prediction technologies, 3D modeling of samples and shifts in consumer behaviour	Potential investments requirements in technology to improve demand forecasting and stock management[iv]
	Reuse	Important potential for reuse (e.g., refurbishment, re-commerce, life extension) to reduce GHG while delivering savings[iv]	Transfer of low-quality textiles from high to low-income regions potentially increasing waste streams[iv]
	Substitute	Potential for reduced environmental impact from new man-made natural fibers (e.g., lyocell, PHA)[iv]	Case-by-case assessment of potential GHG and cost impacts of alternative materials, as well as recyclability
	Re-design	Design for re-use (durability) and design-for-recycling (both chemical and mechanical recycling) prioritising mono-materiality (avoiding blends of different fibre types) and reducing recycling disruptors[viii]	Trends in business models towards fast fashion / short-lived garments; apparel design trends towards material blends

Sources: (i) Systemiq, Breaking the Plastic Wave; (ii) Systemiq, Reshaping Plastics; (iii) Ellen MacArthur Foundation, Catalysing action, 2017; (iv) McKinsey and GFA, Fashion on Climate; (v) Zero Waste Europe. Reusable vs Single-Use Packaging; (vi) Ellen MacArthur Foundation, The New Plastics Economy; (vii) Consumer Goods Forum Golden Design Rules (2021) www.theconsumergoodsforum.com/environmental-sustainability/plastic-waste/key-projects/packaging-design/; (viii) Sorting for Circularity Europe, Fashion For Good (2022) https://reports.fashionforgood.com/report/sorting-for-circularity-europe/

3.2

Mechanical and chemical recycling

Studies indicate that the complementary application of mechanical and chemical recycling has potential to increase recycling rates, increase supplies of high-value (contact-sensitive) recycled PET/polyester, reduce plastic waste and environmental pollution, and reduce GHG emissions for PET/ polyester packaging and textile systems in Europe.

However, researchers and stakeholders express concerns that uncontrolled competition for recycling feedstocks could lead to worse environmental outcomes, if the relative environmental impacts of different technologies are not taken into account.

Environmental assessment of mechanical PET/polyester recycling is well established in peer-reviewed literature. From seven life-cycle assessments (LCA) identified in the literature studying the performance of chemical and mechanical recycling of PET, all studies that included mechanical recycling indicated clear environmental benefits compared to the current manufacturing and/or waste disposal routes in Europe (comparative conventional conditions vary per study) (Exhibit 15, see also Appendix B).

Environmental assessment of chemical PET/polyester recycling is less well established in peer-reviewed literature. However, from the seven LCA studies identified in the literature, six indicate that chemical recycling of PET via depolymerisation has environmental benefits compared to conventional PET manufacturing and waste disposal routes in Europe (incineration or current average mix of landfill and incineration; comparative conventional conditions vary per study). Chemical recycling has higher GHG emissions than mechanical recycling (as established by four out of five LCA studies in which chemical and mechanical recycling technologies are assessed)(Exhibit 15, see also Appendix B).

There is a shortage of published, peer-reviewed and fully accepted LCA studies for different forms of PET/polyester depolymerisation in different geographies. There is also a lack of published research on the extent to which product quality, feedstock tolerance, yield and emissions will change as technologies mature, for both chemical and mechanical recycling and associated sorting/washing processes.

Feedstock suitability for mechanical and chemical recycling is driven by both technical, economic and regulatory considerations. Mechanical recycling into higher-value rPET is particularly suitable for applications such as clear PET bottles where input streams can be closely controlled and EU regulations allow for use of rPET in contact-sensitive applications. New line studies and industry guidance show that repeated or contaminated mechanical recycling loops can degrade the functional properties of the recycled plastic (and its colour), which could present challenges to achieving high levels of bottle-to-bottle recycling[q,30,31]. However, in laboratory conditions, ongoing mechanical recycling of 75% rPET, blended with 25% virgin PET, has been shown to be viable without deterioration of functional properties[14]. The incorporation of additives can also contribute to improving properties of the recyclate[35]. Repeated chemical recycling loops should not degrade the functional properties of the recycled plastic because virgin quality plastic is produced in every recycling loop.

There is a shortage of published research on the technical, economic and regulatory considerations that would guide feedstock suitability for mechanical and chemical recycling. Feedstock suitability information is not published for recycling of mixed-material feedstocks, such as multi-material plastic trays and textiles that blend different synthetic and natural fibres alongside polyester. There are no published and fully accepted feedstock guidelines for optimisation of PET/polyester depolymerisation. Published research is also lacking on the environmental or economic benefits of closed-loop recycling into the same or higher value applications, compared to open-loop recycling into lower-value applications.

A summary of research insights and knowledge gaps for modelling complementarity assessment is shown in Appendix A.

q Only a quarter of PET/polyester is currently being recycled, and so degradation does not yet present a material issue, but should be considered as part of efforts to create a more circular PET system.

Exhibit 15

LCA studies indicate chemical recycling has lower emissions than conventional PET manufacturing and waste disposal routes in Europe and higher emissions than mechanical recycling

Six out of seven LCA studies identified in the literature find that PET chemical recycling has environmental benefits compared to conventional business as usual (BAU) PET manufacturing and waste diposal routes in Europe. BAU comparative methods vary per study, however, consider typical waste disposal routes in Europe (incineration or current mix of landfill and incineration), and convential virgin PET production processes. In five LCA studies in which mechanical and chemical recycling methods were assessed, chemical recycling resulted in higher GHG emissions than mechanical recycling.

Commissioner	Author	Date	Region	Technology	Boundaries	Recycling emissions lower than BAU	Mechanical recycling emissions lower than chemical	Comment
Closed Loop Partners	Environmental Clarity	2021	North America	Various depol.	Cradle to Gate (MRF to polymer product)	✓	✓	
Eastman	Quantis	2022	North America	Methanolysis	Cradle to Gate	✓	N/A	
N/A	Schwarz et al.	2021	Europe	Glycolsis	Polymer production, recycling treatment avoided products	✓	✗	System boundaries do not include processing, waste collection and treatment
N/A	Uekert et al.	2022	North America	Enzymatic Hydrolysis	Cradle to Gate (rPET); Cradle to Grave (disposal) (vPET)	✗	N/A	Enzymatic hydrolysis has significant process differences to other depolymerisation technologies
Ioniqa	CE Delft	2018	Europe	Hydrolysis	Diverse (3 cases)	✓	✓	
Ioniqa	CE Delft	2019	Europe	Hydrolysis	Cradle to Gate	✓	✓	
Petcore Europe	Plastics Europe CE Delft	2012-2019	Europe	Depolymerisation *Not specified*	Cradle to Gate	✓	✓	

Note: Additional processing (e.g., conversion to terephthalic acid and repolymerisation) would be required for synthesis of PET with the majority of current infrastructure[36].
N/A: LCA studies do not include mechanical recycling as part of the assessment.

Conclusion

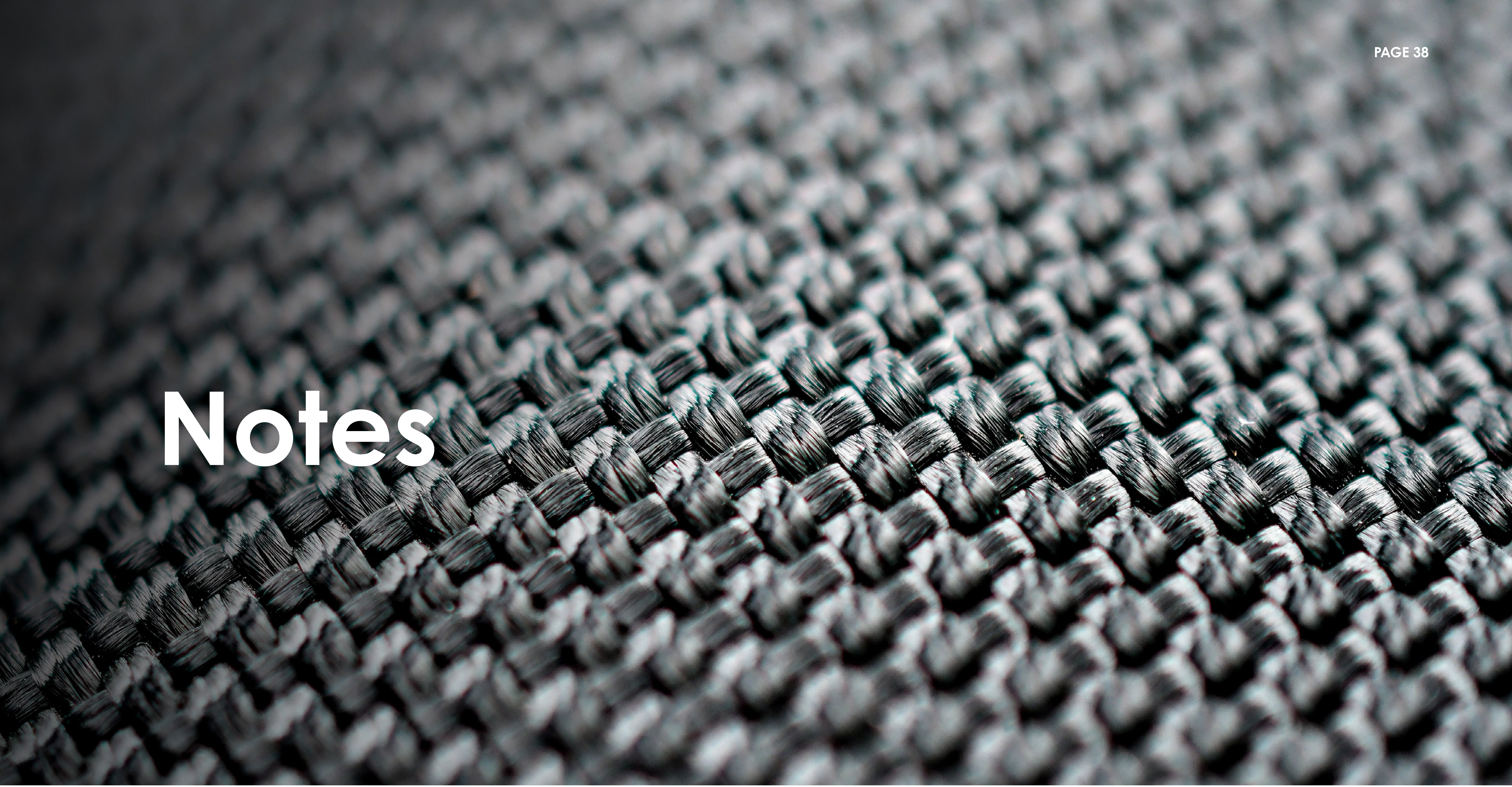
The strong recycling performance of clear PET beverage bottles in some European countries has given PET/polyester a reputation as a "circular plastic system". The synthesis of research studies in this report challenges this assertion for PET beverage bottles and does not support it for the PET/polyester system as a whole. However, the research studies also highlight the relative advantages of PET/polyester for both mechanical and chemical recycling, and the opportunity for scale-up of mechanical recycling, chemical recycling and reuse – to reduce waste and greenhouse gas emissions, enhance supplies of high-value recycled materials and decouple the PET/polyester system from fossil-fuel-based feedstocks.

Published research insights provide useful signposts for designing a new system based on complementarity. However, this synthesis study identifies important knowledge gaps. A system model and scenario assessment tool does not exist for PET/polyester in Europe and would provide valuable insights and guidance to industry and policy-makers, provided that it is designed to take into account knowledge gaps and uncertainties.

This model will be the subject of the next phase of this project, building on the research studies identified in the paper and a comprehensive system analysis to enable system-thinking and comparisons of different complementarity scenarios and dialogue between stakeholders. The model uses material flow analysis to track flows of PET across the plastic system, and will include an estimation of emissions for each step of the system. Outputs will also include the volume of PET reaching end of life via landfill, incineration, mismanaged into nature, and volume ending in circular solutions such as mechanical and chemical recycling. Pre-defined scenarios will be populated in the model, to understand the impact of complementary molecular and mechanical recycling scenarios relative to uncomplementary scenarios. Outputs and insights from the model will be delivered in a second White Paper to be released in 2023.

This synthesis study reflects the available published studies and interpretations of the study team with guidance from our independent Steering Group and expert advisers. The study team would welcome questions, challenges, relevant data points and information about published or ongoing studies that are not referenced in this paper[r].

r Contact us at plastic@systemiq.earth



Notes

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- PET Market in Europe – State of Play (Eunomia)
- PET Market in Europe – State of Play (Eunomia)
- How Circular is PET? (Eunomia)
- ReShaping Plastics (Systemiq)
- Fashion on Climate (McKinsey + Global Fashion Agenda)
- Non-technical challenges to non-mechanical recycling (Wrap)
- Climate impact of pyrolysis of waste plastic packaging in comparison with reuse and mechanical recycling (Zero Waste Europe)
- Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate) (PET) Packaging Management Strategies in the EU (Bassi S. et al.)
- Chemical recycling: insights based on LCA (Delft University)
- Neste RE for more sustainable polymers and chemicals (Neste)
- Plastic Flow 2025 – Plastic Packaging Flow Data Report (Wrap)
- Wrap UK plastic packaging flows (Wrap)
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- Research and identification of textile plants globally – focusing on fibre-to-fibre recycling for the fashion & textile industry (LifeStyle & Design Cluster)
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- Vision of a circular economy for fashion (Ellen MacArthur Foundation)

Glossary

Chemical recycling
Processes that break down polymers into individual monomers or other hydrocarbon products that can then serve as building blocks or feedstock to produce polymers again.

Circularity
Circularity is a measure of resource efficiency, i.e., the degree to which (re)used materials replace new virgin materials. In this study, the circularity metric is defined as the share of plastic utility that is either reduced, substituted by circular materials, or recycled mechanically or chemically. It excludes plastic disposed of in a linear fashion or plastic entering stock.

Contact-sensitive
Materials subject to specific regulations in the European Union and intended to come into contact with food or skin (e.g., cosmetic or pharmaceutical purposes).

Design for Recycling (D4R)
The process by which companies design their product and its packaging to be recyclable.

Extended Producer Responsibility (EPR)
Schemes that enable producers to contribute to the end-of-life costs of products they place on the market.

Feedstock
Any bulk raw material – virgin or secondary – that is the principal input for an industrial production process[37]. Currently, plastic is largely produced from petrochemical feedstock, i.e., from fossil fuels.

Incineration with energy recovery / Waste-to-energy
Waste-to-energy refers to the incineration of (plastic) waste with recovery of generated energy. Waste-to-energy schemes use plastic waste as a fuel to generate power.

Landfill
Specially engineered site for disposal of solid waste on land. The waste is generally spread in thin layers which are then covered with soil[38].

Lever
A specific solution modelled within a system intervention.

Mechanical recycling
Operations that recover after-use plastics via mechanical processes (grinding, washing, separating, drying, re-granulating, compounding), without significantly changing the chemical structure of the material[37].

Pellet
Standard raw material used in plastic manufacturing. Pellets are tablets or granules of uniform size, consisting of resins or mixtures of resins with compounding additives which have been prepared for moulding operations by extrusion and chopping into short segments[38].

Plastic
Material which contains, as an essential ingredient, a high polymer and which at some stage in its processing into finished products can be shaped by flow[39].

Plastic demand
Plastic demand is defined as the volume of plastic utility minus the volume of plastic utility fulfilled by reduce and substitute levers.

Recyclate
Recyclate is the output material of recycling processes that can be directly used as a secondary raw material for plastic conversion.

Reuse models
Replacement of single-use packages with reusable items owned and managed by the user or by services and businesses which provide the utility (New Delivery Models).

Sorting
Physical processing techniques and processes to separate materials in waste streams. Sorting is typically performed in Material Recovery Facilities (MRFs) or specific Plastic Recovery Facilities (PRFs). Sorting can be performed automatically with sorting technologies or manually.

Virgin plastic
Direct resin produced from a petrochemical feedstock, such as natural gas or crude oil, which has never been used or processed before.

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Appendix A

The synthesis identified a number of research insights and knowledge gaps that are relevant for this system-level complementarity analysis

Reduction, reuse, substitution and re-design

Research insights:

- Reduction and reuse strategies offer high potential for lowering negative environmental impacts but will not be feasible or beneficial for all PET/polyester product applications
- Substitution from PET/polyester to other materials could be environmentally beneficial in some cases but in many cases can be environmentally harmful.[27] The same is true for substitution into PET/polyester from other materials, which can have a positive environmental impact in some cases
- Design for recycling is needed to unlock the full potential of both mechanical recycling and PET/polyester depolymerisation

Knowledge gaps:

- The size of the reduction, reuse and substitution opportunity for PET/polyester applications (bottles, trays, textiles), including substitution into PET/polyester from other materials, where this would be environmentally beneficial

Appendix A

Chemical and mechanical recycling

Research insights:

- Mechanical recycling is particularly suitable for applications such as clear PET bottles where input streams can be closely controlled and EU regulations allow for use of rPET in contact-sensitive applications. Repeated or contaminated mechanical recycling loops for bottles can degrade the functional properties of the recycled plastic (and its colour)
- PET/polyester depolymerisation can process some hard-to-recycle products into virgin-equivalent rPET/polyester, which can be suitable for contact-sensitive applications regardless of feedstock type. Repeated chemical recycling loops should not degrade the functional properties of the recycled plastic
- Multiple studies indicate lower GHG emissions from both mechanical and chemical recycling of PET/polyester compared to energy-from-waste incineration and landfill, taking into account avoidance of virgin plastic production
- Multiple studies indicate lower GHG emissions from mechanical recycling of PET compared to chemical recycling via depolymerisation

Knowledge gaps:

- Published information on the effectiveness, limitations and feedstock tolerance of mechanical recycling for polyester textiles and trays
- Published information on the ranges in quality of mechanically recycled PET plastic and degradation of functional properties (including colour) in multiple loops of mechanical recycling without addition of virgin input, assessed in real-world conditions (e.g., potential contamination at each loop)
- Regulatory trends, including regulatory treatment of chemical recycling and regulations governing contact-sensitive use of recycled PET from mechanical and chemical recycling
- Published information on the effectiveness, limitations and feedstock tolerance of chemical recycling for polyester textiles and trays
- Published and fully accepted GHG benchmarks for different forms of PET/polyester depolymerisation
- Published and fully accepted yield performance that is comparable between different forms of chemical recycling
- Environmental or economic benefits of closed-loop recycling into the same or higher value applications compared to open-loop recycling into lower-value applications
- The extent to which product quality, feedstock tolerance, yield and emissions will change as technologies mature, for both chemical and mechanical recycling and associated sorting/washing processes.

Appendix B

Summary table of LCAs on PET Depolymerisation (Part 1 of 2)

		Eastman/Quantis	CLP/Env. Clarity	Ioniqa/CEDelft 2018	Ioniqa/CEDelft 2019
Outcomes	**GHG emissions of recycling lower than BAU**	✓	✓	✓	✓
	GHG emissions of Mechnical R. lower than Molecular		✓	✓	✓
Study overview[1]	**Research goal**	Compare footprint of DMT made by methanolysis to fossil-based alternative	Evaluate multiple & diverse waste plastic recycling technologies	Evaluate Ioniqa's tech. against conventional waste processing	Compare depol. of PET trays vs mechanical recycling vs combustion
	Model Approach	ISO 14040/44 LCA study; Critical review by third-party panel of LCA experts	ISO 14040/44 LCA study; Critical review by third-party panel	Simplified attributional LCA, with focus on climate impact or CO_2 ratio	Unspecified *(refers to confidential previous Ioniqa study)*
	Analysed system	Eastman conventional DMT reference vs Eastman methanolysis technology	Study of 10 molecular recycling technology processes	Ioniqa's tech vs PET from petroleum vs mechanical rec. & combustion in EFW[c]	Unspecified *(refers to confidential previous Ioniqa study)*
	Value Chain steps (system boundaries)	Cradle: Raw material extraction (virgin); end of previous life (waste) Gate: DMT/EG mfg.	From MRF[a] to WPRT[b] Avoided sys.: EOL (landfill 83%; incineration 17%); virgin: raw material to mfg.	3 systems with varying boundaries. Start from collection of recycling; End at rPET or Bottle	Unspecified *(refers to confidential previous Ioniqa study)*
	Data Basis	BaBi v.9.2.1.68 software Combined GaBi data sets & internal Eastman LCAs	Std. data provided by WPRTs; verified by 3 party chem. engineering analys.	Unspecified *(complete report is confidential)*	Unspecified *(refers to confidential previous Ioniqa study)*
	Time horizon & region	2020 with expected 2023 feedstock; North America	Average 2019 U.S. electric grid	Europse published on 2018. Data of analysis unspecified	Unspecified *(refers to confidential previous Ioniqa study)*

Appendix B

Summary table of LCAs on PET Depolymerisation (Part 2 of 2)

		Uekert et al. 2022	Schwarz et al. 2021	Petcore
Outcomes	**GHG emissions of recycling lower than BAU**	✗	✓	✓
	GHG emissions of Mechnical R. lower than Molecular		✗	✓
Study overview[1]	**Research goal**	Evaluate enzymatic hyd. against other recycling and synthesis processes	Assess performance of 10 recycling technologies with varying TRL levels	Evaluate PET depol. Against conventional measures
	Model Approach	Process-based LCA. SimaPro with TRACI2.1 U.S. 2008 and AWARE methods	LCA Matrix model. Data & param. Combined in functions (R Studio 3.6.0 & ggplot2)	Avg. from LCA studies based on process models for industrial scale ops.
	Analysed system	Enzymatic PET hyd. process by Aspen Plus; LC inventories for expansions from system	25 polymers with 0.2Mt/year demand; selection of top rec. tech	Not specified
	Value Chain steps (system boundaries)	Cradle: Feedstock extraction; Gate: rPET production; Grave: vPET disposed (20% inc. 80% landfill)	Polymer granulate production, recycling treatment impacts and avoided products	Cradle to Gate. collection, sorting, pretreatment; excludes avoided CO_2e produced by incineration
	Data Basis	LC inventories from Ecoinvent 3.3; US & global databases	Materials, emissions & fuels from ecoinvent 3.4. Europe data [RER] with SimaPro 8	PlasticsEurope Ecoprofiles (Ethylene 2012, BTX 2013, PTA 2016, PET 2017), SRP Ecoprofile 2017, CE Delft 2019
	Time horizon & region	North America	Europe (diverse; from different sources)	Europe